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THE INTRANEURAL TOPOGRAPHY OF THE RADIAL, MEDIAN AND ULNAR NERVES.

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OUR knowledge concerning the intraneural topography of peripheral nerves is far from being definite or precise. Some claim that a nerve is but the aggregation of its branches which are held together by a connective tissue framework so that the component funiculi retain their identity and relative positions throughout their intraneural course. Others contend, and it is now generally accepted, that the intraneural funicular pattern involves repeated plexus formations of such bewildering complexity as to exclude the possibility of groups of fibres being confined throughout their course to a particular funiculus or quadrant of the nerve. Information concerning the nature of the funicular intercommunications is, however, surprisingly incomplete and the mere demonstration of an intraneural plexus is not sufficient to justify the conclusion that the interlacement of funiculi effects a reorientation as well as a funicular redistribution of fibres since, despite the participation of funiculi in plexus formations, the fibres of a branch could conceivably remain localized in the nerve. The investigation which forms the subject of this report was undertaken with the object of elucidating the detailed intraneural topography of the radial, median and ulnar nerves with especial reference to the following hitherto undescribed features: (1) the distance over which fibres composing individual muscular and cutaneous branches retain their identity and position in the nerve trunk and the precise nature and extent of the redistribution of the fibres which is brought about by the division and anastomosis of funiculi; (2) whether the funicular rearrangement implied in the plexus principle brings into relationship fibres innervating tissues of corresponding type and function or whether it is responsible for their dispersal; (3) whether all the fibres in a funiculus or only a proportion of them are involved in any process of redistribution and, in the event of the latter, whether the exchange is indiscriminate or involves fibres of related type.

Literature.

The course of fibres within the nerve and the funicular pattern have been variously studied (1) by dissection and histological examination (Bardeen, 1906; Stoffel, 1913 and 1915; Putti, 1916; Heinemann, 1916; Barile, 1917; Langley and Hashimoto, 1917; Compton, 1917; Dustin, 1918; McKinley, 1921; Goldberg, 1924; and O'Connell, 1936); (2) by correlating (*a*) the peripheral response to electrical stimulation with the funiculus or point on the circumference of the nerve stimulated (Marie Meige and Gosset, 1915; Langley and Hashimoto, 1917; Kraus and Ingham, 1920*a*, *b*; and McKinley, 1921), and (*b*) the peripheral loss of function with the site of partial nerve injury (Sherren, 1907; and Dejerine, Dejerine and Mouzon, 1915); and (3) by tracing the funicular distribution of the Wallerian degeneration following partial division of a nerve (McKinley, 1921; and Kilvington, 1940).

Anatomical and histological examination.—Bardeen (1906), from an examination of fœtal and adult material, concluded that nerve fibres follow a much more direct course in the nerve than any funiculi and on the basis of his findings constructed a schematic cross-section of the femoral, obturator and sciatic nerves on which were outlined the regions occupied by the fibres of the chief motor and sensory branches. The approximate areas occupied by the main bulk of each spinal segment were also shown. No attempt, however, was made to establish the intraneural topography for the whole length of any nerve nor was the intraneural plexus specifically referred to as such.

Stoffel (1913, 1915) developed the conception of the simple "cable structure of nerves." He regarded the proximal portion of the nerve as the systematic aggregation of its peripheral branches so that at proximal levels the funiculi representing individual peripheral branches could be precisely identified. On the basis of his observations he designed operative procedures for the relief of spastic conditions and the residual palsies of anterior poliomyelitis. Both Putti (1916, for the lateral popliteal) and Barile (1917) favoured such a discrete and rigid intraneural localization.

The plexiform character of the intraneural funicular pattern has been established conclusively for the median, ulnar and sciatic nerves, by Heinemann (1916); for the radial, median and ulnar nerves, by Dustin (1918); and for the sciatic nerve, by Compton (1917), Langley and Hashimoto (1917), McKinley (1921) and Goldberg (1924). O'Connell (1936) did not investigate these nerves but demonstrated the plexus in others. These investigations, however, accomplished little more than the demonstration of a funicular plexus of varying complexity though it was also shown

that branches could be traced for variable, but often considerable, distances along the nerve proximal to the site of branching. It was believed, however, that the intercommunications were so intricate and complicated as to exclude the possibility of any continuous localization of branches along the nerve trunk though Langley and Hashimoto (1917) added a proviso that "whilst the connections of the bundles centrally of the plexus with those peripherally of it cannot be determined by simple inspection, it is not unlikely that some fibres keep their lateral, median or other position in passing through the plexus since a complete crossing of fibres, apart from twisting of the whole trunk, seems meaningless."

The electrical stimulation of exposed nerves.—Marie, Meige and Gosset (1915) and Kraus and Ingham (1920*a*, *b*) stimulated different points on the circumference of human nerves, which had been explored at various levels, and correlated the consequent muscular contraction with the particular quadrant stimulated. Both described a precise and constant intraneural localization of fibres which will be referred to later. According to Kraus and Ingham "a review of the results for a given muscle at various levels brings out one point with certainty—the course is a straight one from the point where the nerve has been made up by its contributing segments to the point of offset of the fasciculi as a branch. An exception to this was uniformly found in one instance in which it was to be expected, namely, the fasciculi to the pronator radii teres." It is felt, however, that the reported observations do not justify such a conclusion—particularly in view of a statement in their account to the effect that stimulation of the proximal part of the nerve did not, as a general rule, cause contraction of muscles supplied by its distal portion. They were also unable to correlate the funicular composition and pattern at any level wtih the localization elicited by electrical stimulation and it is unwise to draw morphological conclusions from physiological evidence alone. Furthermore results obtained by this method are open to criticism in view of the possible diffusion of the stimulus through the nerve which might activate fibres well beyond the point directly stimulated.

Langley and Hashimoto (1917) divided the peroneal nerve of the cat at the knee, identified and isolated the seven small bundles of which the nerve was composed and found, by stimulation, that each bundle supplied a separate region. In this way they showed that at peripheral levels the branches for different muscles may be arranged to a greater or lesser extent in different bundles in the nerve. McFinley (1921) repeated this experiment in the dog but divided the sciatic nerve in the region of the ischial tuberosity. Stimulation of each bundle in the sciatic tibial and sciatic

common peroneal resulted in the contraction of all the muscles supplied by the division containing that bundle. From this it was concluded that no localization of fibres existed. This experiment, however, only proved that *at the level of stimulation* each bundle contained representatives of all the muscular branches of the division in sufficient concentration to give a response. The significance of the different response to stimulation reported by Langley and Hashimoto and by McKinley will be discussed later.

The study of partial nerve lesions.—The Dejerines and Mouzon (1915) correlated the distribution of the motor and sensory loss in partial nerve lesions with the site and extent of the injury as estimated at operation. Their observations favoured the conception of an intraneural localization of fibres. Such studies, however, provided no information concerning the course and behaviour of the fibres proximal and distal to the level of the lesion nor was any correlation with the funicular composition and pattern possible.

Sherren (1907) has stated that a third of a nerve trunk can be divided without producing any demonstrable motor or sensory loss. Much depends, as will be shown later, on the level of the section and which third of the nerve is divided. Though opposed to the conception of a discrete and rigid localization, Sherren believed that in certain nerves the fibres were arranged in a well-defined order and that "if the incision cuts into the nerve just above the point of origin of a branch the signs of complete division of that branch are produced."

The distribution of Wallerian degeneration.—The distribution of the Wallerian degeneration following high and partial nerve section was studied by McKinley (1921, sciatic nerve in the dog) and Kilvington (1940, median and ulnar nerves in the cat). Both reported that the degenerated fibres were widely distributed over the nerve at distal levels and were usually demonstrable in all of the peripheral branches. This observation was interpreted as evidence against any possible intraneural localization. Their particular experiments, however, would not reveal the fact that fibres which were widely disseminated over the funiculi at the level of the lesion could be collected together and sharply localized at more distal levels. In arriving at their conclusion such a possibility was apparently disregarded.

Material and Methods.

A recent investigation of the blood supply of human peripheral nerves (Sunderland, 1945*a*) involved the examination of serial microscopic sections of the larger nerves in 37 adult dissecting room subjects. Segments

of the radial nerve, 1 cm. in length, were taken in the brachio-axillary angle, at the entrance to and exit from the spiral groove, in the groove and in the furrow between the brachioradialis and brachialis muscles. The last segment included the terminal portion of the nerve and its two divisions. Ten segments, each 1 cm. in length, were cut from the median and ulnar nerves. The first section was taken in the axilla: the fifth at the elbow and the tenth at the wrist. Of the remaining segments, the second, third and fourth were evenly spaced between the axilla and elbow, and the sixth, seventh, eighth and ninth, between the elbow and the wrist. Each segment was fixed in the usual manner and embedded in paraffin. Serial transverse sections, 15 microns in thickness, were cut from each block and stained with hæmatoxylin and eosin. This material proved suitable for a study of the number, size and general arrangement of the funiculi at successive levels.

Owing to the frequent, irregular and unpredictable changes in the funicular plexus pattern the fibres comprising the branches could not be accurately traced along a nerve for any great distance by this method and it became obvious that detailed information concerning the intraneural topography of branches could only be obtained by serially sectioning the entire nerve. For this purpose specimens of the radial (one), median (one) and ulnar (two) nerves were dissected throughout their course, their branches accurately identified, and each branch sectioned immediately beyond its origin in order to establish its funicular pattern. The site of origin of each branch was fixed by measurement with reference to the humeral epicondylar and radial styloid levels and the site of terminal division of the nerve. In addition landmarks were established along the nerve to permit the correct identification of quadrants in the serial sections. Each nerve was divided into segments which were treated, sectioned at 25 μ from below upwards, and stained in the manner previously described. Every tenth section was mounted and the others retained for reference. In addition a full-term fœtal arm was serially sectioned between the axilla and the metacarpophalangeal joints and the sections stained with hæmatoxylin and eosin.

The sections were enlarged on a microprojector, drawn and the diagrams arranged in serial fashion. The funiculus or funiculi comprising each branch were given a designatory marking and traced into and proximally along the nerve as represented by the transverse sections. In this way the position and fibre-content of a funiculus at any particular level and the manner in which its fibres were redistributed could be accurately established.

Additional information relating to the grosser features of the intraneural topography of the peripheral branches was obtained by microdissection of a further 20 specimens of each nerve in which the peripheral branches were traced as far proximally along the nerve as was practicable.

In the descriptions which follow all branches have been regarded as proceeding from the structures they innervate towards, into, and along the nerve so that the latter has been synthesized in terms of its branches. Similarly in the discussion relating to the intraneural behaviour of funiculi the direction of change is from distal to proximal.

General Features.

The number, size, composition and behaviour of the funiculi determine the funicular pattern and each of these features will be discussed in turn.

Number.

There was no constant or characteristic pattern for any nerve though Dustin's (1918) classification of three types with few, many and a medium number of funiculi is a convenient one. The number of funiculi varied greatly from nerve to nerve and individual to individual at any given level, and at the same level on the two sides of the body. As Dustin (1918) pointed out, however, if the pattern conforms to one of the three types on one side it usually corresponds on the other. The number of funiculi, counted at millimetre intervals over the distal 5 cm. of the radial nerve and expressed in centimetre segments, is given to illustrate the rapid changes which may occur from level to level so that sections a few millimetres apart may show marked differences in the number of funiculi.

1st cm.	10	10	11	10	10	11	10	10	11	10
2nd cm.	11	10	13	12	12	10	12	14	13	13
3rd cm.	11	14	15	12	15	16	14	15	14	15
4th cm.	12	12	12	14	13	11	10	13	14	8
5th cm.	13	12	8	8	10	11	15	14	8	11

Funicular intercommunications and divisions rarely occurred within, though they were common at 0·25 mm. intervals. Consequently reference to the number of funiculi at successive intervals exceeding 0·25 mm. will not afford an accurate reflection of their behaviour since, as frequently occurs, two bundles may anastomose and another divide in such an interval thereby leaving the numerical picture undisturbed.

According to Dustin (1918), funiculi show a tendency to multiply in the neighbourhood of the origin of branches and to fuse at points between them. On the basis of this observation he divided nerves into two types, first those with few funiculi and prominent nodal points of fusion and secondly those composed of a large number of funiculi with very few nodal points. This observation was not confirmed in the present study in which

the funiculi, excluding those about to leave in the branch, showed no constant or significant tendency to either reduction or multiplication at the site of branching.

Radial nerve.—A funicular count in the axilla and brachio-axillary angle, spiral groove, and intermuscular furrow varied from 11 to 40, 1 to 11, and 4 to 24 respectively. The large number in the first situation was accounted for by the numerous branches to the triceps which accompanied the nerve, often for considerable distances, as collaterals. In each nerve examined the number in the axilla and brachio-axillary angle exceeded that in the furrow which in turn exceeded that in the spiral groove. The marked reduction, frequently to a single bundle, in the number in the spiral groove was a striking feature. The considerable variation in the number of funiculi as observed in transverse sections of a nerve at eight different levels is illustrated in text fig. 1.

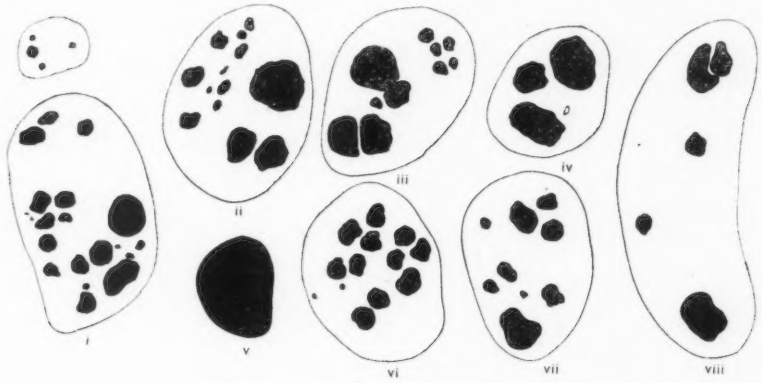

FIG. 1.

Median and ulnar nerves.—The number of funiculi observed at the wrist, in the forearm, at the elbow, and in the distal and proximal halves of the upper arm was as follows (the figures in brackets represent the number customarily present):

	Median nerve	*Ulnar nerve*
Wrist	20 to 35	20 to 35
Forearm	4 to 18 (11 to 16)	9 to 27 (13 to 16)
Elbow	14 to 24	2 to 9 (4 to 7)
Upper arm distal	4 to 19 (7 to 12)	4 to 25 (8 to 12)
Upper arm proximal	3 to 13	1 to 14 (5 to 8)
Medial root	3 to 10	
Lateral root	5 to 8	

Dustin (1918) observed that the ulnar nerve is habitually composed of a larger number of funiculi than the median. The findings in the present investigation, which were as follows, provided evidence to the contrary:

(i) At the wrist the number of funiculi corresponded in the two nerves.

(ii) At the elbow the number in the median nerve exceeded in every specimen that in the ulnar while in the proximal half of the upper arm also the number was usually greater in the former than in the latter.

(iii) In the forearm and in the distal half of the upper arm the numbers favoured one or the other or neither.

(iv) In each nerve the funiculi were most numerous at the wrist. They were least numerous in the axilla and proximal half of the upper arm and also in the epicondylar groove in the case of the ulnar nerve.

Size.

The anastomosis and division of funiculi were responsible for variations in the size and number of the bundles and these two features were inversely related at any level.

The largest funiculi were observed in the spiral and epicondylar groove sections of the radial and ulnar nerves respectively.

The size of the funiculi appeared to bear no relationship to the site of branching.

Radial nerve.—In general, the radial nerve was composed of a large number of small funiculi in the axilla and angle, of a small number of large bundles in the spiral groove and of a medium number of small and large funiculi in the intermuscular furrow. The largest funiculi were observed in the spiral groove.

Median and ulnar nerves.—The median and ulnar nerves were customarily composed of a large number of small funiculi at the wrist, of both medium-sized and small funiculi in the forearm and of a combination of large, medium and small in the upper arm.

Cross-sectional Area of Individual Branch Fibre Systems Within the Nerve.

Though the cross-sectional area of a funiculus is not an accurate measure of its fibre-content, since the degree of myelination and the amount of the intrafunicular connective tissues are contributing factors, it may, nevertheless, be accepted as an indication of the proportionate area occupied by its constituent fibres in the entire nerve. The cross-sectional area of the funiculi devoted to individual motor and sensory branches before interfunicular mixing occurred was estimated by means of a planimeter. The following values, expressed in terms of the total cross-sectional

area occupied by the combined funiculi in each nerve, are approximate only.

Radial nerve (below triceps and dorsal cutaneous of forearm).			
Superficial radial	23/100	Total cutaneous	23/100
Posterior interosseous	45/100		
Extensor carpi radialis brevis	8/100		
Extensor carpi radialis longus	8/100		
Brachioradialis	13/100		
Brachialis	3/100	Total muscular	77/100
Median nerve.			
Terminal cutaneous	61/100		
Palmar cutaneous	3/100	Total cutaneous	64/100
Terminal muscular	9/100		
Flexor digitorum sublimis	8/100		
Anterior interosseous	7/100		
Pronator teres	4/100		
Proximal common flexor	5/100		
Distal common flexor	3/100	Total muscular	36/100
Ulnar nerve.			
Terminal cutaneous	33/100		
Dorsal cutaneous of hand	22/100	Total cutaneous	55/100
Terminal muscular	20/100		
Flexor digitorum profundus	8/100		
Flexor carpi ulnaris	13/100	Total muscular	41/100
Branch to the ulnar artery	4/100	Total arterial	4/100

Fibre Composition of Funiculi.

Funiculi were composed of (i) muscular fibres from a single muscle, from a group of muscles having the same or similar actions, or from a number of muscles which were not functionally related; (ii) cutaneous fibres, and (iii) varying combinations of muscular and cutaneous fibres.

The source of the fibres contained in a funiculus depended on the level at which an analysis was made. At the axillary outlet it was usual for the majority of the funiculi to contain representative fibres from most, if not all, of the peripheral branches. At lower levels a regrouping of the fibres was gradually effected whereby the muscular and cutaneous elements came to occupy different funiculi. A further extension of this process ultimately resulted in the appearance of groups of funiculi in which the nerve fibres were destined solely for specific cutaneous branches and muscle fibres first of the same functional group and later of the same muscle.

The Behaviour of Funiculi.

The funiculi were subjected throughout the length of the nerve to anastomoses, divisions and intraneural migrations. They were more compactly arranged in some regions than in others depending upon the looseness of

the supporting epineural framework and the amount of fat which it contained. As a rule the nerve was thinner where there were few large funiculi than where the bundles were small and numerous since in the latter case the amount of supporting connective tissue was necessarily greater and naturally added considerably to the cross-sectional area of the nerve.

The intraneural shift or migration of funiculi.—Before and between anastomoses, which always involved adjacent funiculi, the latter usually pursued a direct course along the nerve so that the intraneural shift of any participating bundle was over very short distances only. On occasions, however, migrations were observed in which individual bundles and bundle groups proceeded for considerable distances over the surface of, or obliquely through, the nerve as well as along it. In this way their constituent fibres were transported, *en masse*, from one quadrant to another. The behaviour of the extensor carpi radialis brevis and large thenar muscular (median nerve) bundles illustrate this feature. The former bundle ascended obliquely through the radial nerve from its medial to its lateral surface while the latter, at the wrist, migrated from a mid-anterior to a postero-radial position. Other examples may be found in the accompanying charts.

Where a muscle was innervated by multiple branches entering different aspects of the nerve at different levels the bundles representing the proximal branches migrated considerable distances through or over the nerve in order to reach, and anastomose with, those containing fibres which had entered by more distal branches. The behaviour of the proximal flexor digitorum sublimis branch bundle of the median nerve is a case in point. Here the bundle moved across the anterior surface of the nerve from the radial to the ulnar margin in order to reach and anastomose with those bundles containing the distal flexor digitorum sublimis fibres.

Again there was a tendency for funiculi from different muscles having similar actions to anastomose with one another before participating in further intercommunications. This often led to a considerable intraneural shift of one or other or both bundle systems before a union was effected. The behaviour of the funiculi of the extensores carpi radiales is illustrative of this type of migration.

The anastomosis and division of funiculi.—The observed plexus formations may be conveniently reduced to three fundamental types. In the first, plexus formations occurred between bundles whose constituent fibres were derived entirely from one branch and were consequently

localized to individual bundle groups. The anastomoses involved adjacent bundles in the group but not all at the same level. The scattering and intermingling of fibres thereby effected involved fibres from the same source so that these remained confined within the limits of the bundle group. An example of this type of intercommunication is provided by the superficial radial bundle group which pursued an independent and localized course for 46 mm. over which distance there were 23 changes in the bundle pattern. The bundles of branches entering at proximal levels may participate in this form of exchange only, owing to the fact that they reach the brachial plexus before further intercommunications can occur. In these circumstances the degree of localization obtaining is sharp while the bundles are usually superficially placed and therefore more liable to injury.

In the second type the members of one bundle group anastomosed with the adjacent bundles of another and this involved a blending of the fibres of the two originally distinct groups. The intermingling was effected very gradually since the anastomoses involved only immediately adjacent bundles. This meant that fibres could only be widely dispersed over the more remotely situated bundles of the groups by slow transference through a number of bundles so that complete mixing occurred only after considerable distances. The intraneural shift of fibres was increased by this process but even when the intermingling was completed, unless individual migrations had increased the range of redistribution, the fibres of the two systems were still confined to that portion of the nerve originally occupied by the two bundle systems. In this process one bundle group may proceed without change of position while the fibres of another are progressively added to it. Thus in addition to promoting the intermingling of fibres from different sources, this type of intercommunication may lead, not to an exchange of fibres but to the absorption of the constituent fibres of one bundle group into the bundles of another. Examples of this type of intercommunication are provided by tracing the fate of the terminal cutaneous bundle groups of the median and ulnar nerves and by studying the manner in which, in the median nerve, the majority of the second interspace digital cutaneous fibres were gradually added to the third interspace bundles.

This third type of intercommunication was observed at proximal levels and was responsible for the most widespread dispersal of the fibres. Here, neighbouring bundles composed of different branch fibres, which had been intermingled at distal levels, repeatedly divided and anastomosed. The fibres were in this way progressively but gradually diffused over

the funiculi until considerable scattering had been effected though this was usually only observed at high levels.

It is of interest that the intercommunications did not invariably lead to a dispersal of the fibres but that in some cases the process was actually reversed so that fibres, which had been widely scattered over several funiculi at distal levels, were regathered into one or two bundles. For example, the terminal muscular and cutaneous fibres of the serially sectioned ulnar nerve which were distributed over several funiculi below the 153 mm. level were regathered, at that level, into a single bundle.

The fusion of funiculi may be followed by the complete or partial intrafunicular mixing of the fibres or the elements of the two original funiculi may remain segregated. In the latter event the fibres may retain a constant position within the funiculus or move, *en bloc*, within it. The intrafunicular behaviour of fibres, which could not be satisfactorily investigated by the methods employed in the present study, determines their subsequent fate when the funiculus divides. Impending division was indicated by the appearance of an intrafunicular septum along which cleavage occurred. The intrafunicular arrangement of the fibres and the line of the septum governs the fibre composition of the new funiculi.

These intercommunications took place gradually along the entire nerve —the maximum length of nerve seen with a constant pattern was 15 mm. (ulnar nerve) though individual bundles and bundle groups pursued longer courses. The intercommunications were of such a nature that the dispersal of fibres which they occasioned was gradual and, at any one level, produced only a minor degree of intraneural shift. It was the summation of the changes at successive levels, and not that at any one level, which was ultimately responsible for the widespread scattering of fibres. At proximal levels the constituent fibres of the bundles were arranged in varying combinations and proportions though no single bundle necessarily contained fibres from all the branches. The funicular distribution of the branch fibres at different levels is shown in the diagrams of the transverse sections illustrating the intraneural topography of the nerves.

Despite the changing plexiform character of the funicular pattern, fibres from peripheral branches pursued a localized course in the nerve for variable, though often considerable, distances. Such a localization involved all or the majority of the fibres of any branch. It is evident, therefore, that the redistribution implied in the plexus principle is, in the first instance, local and not general. The scattering of fibres occurs gradually and only as the intercommunications are repeated so that widespread intermingling and dispersal of fibres is achieved only after they

have ascended considerable distances along the nerve. This conception of the fundamental character of the plexus, and the type and extent of the redistribution of the fibres to which it gives rise, is of considerable importance and has not received the attention it merits. The demonstration, by dissection and the examination of incomplete serial sections, of an intraneural plexus and of a continually changing intraneural funicular pattern is no proof that a complete reorientation or redistribution of fibres is effected by the intercommunications or that all traces of localization are thereby erased. Conclusions based on such investigations alone have given very misleading results.

The Composition of the Funicular Pattern in Terms of the Peripheral Branching of the Radial, Median and Ulnar Nerves.

Since the intrafunicular behaviour and fate of fibres could not be accurately observed by the methods here employed it has been assumed, for the purpose of tracing the intraneural course of fibres of peripheral branches, that the fusion of funiculi was followed by an intermingling of their constituent fibres in the newly formed funiculus and that when the latter divided the daughter-bundles carried representatives of all the original fibres contained within the parent bundle. That this is not necessarily so has been previously pointed out but it should be noted that, on this basis, the redistribution indicated is the maximum possible.

In recording the number of changes of pattern observed throughout the length of a nerve, or along any particular length or bundle group of it, the figure given does not cover every fusion and division since a variation in the funicular pattern at two successive levels was registered as a single change regardless of the number of fusions and divisions responsible for the variation.

In order to avoid confusion the surfaces and margins presented by each nerve, in terms of which the intraneural topography of their branches is expressed, are indicated in each section.

The detailed arrangement has been described in one specimen of each nerve only. The site and order of branching which are known to be variable features must influence the intraneural topography with the result that variations in the latter are inevitable. Such variations, however, concern detail only and do not affect the general plan.

Radial Nerve.

At its termination the nerve is flattened from before backwards and presents medial and lateral margins. Between the epicondyle and the point where it pierces the septum the nerve is contained in the furrow

between the brachioradialis and extensor carpi radialis longus laterally and the brachialis medially. This gives the nerve an oval outline with anterior and posterior poles and superficial or lateral, and deep or medial, surfaces. On entering the spiral groove the lateral surface becomes posterior, superficial or muscular and the medial surface anterior, deep or bony while the margins of the flattened nerve are correspondingly altered to supero-lateral and infero-medial; this arrangement obtains as high as the brachio-axillary angle.

In the serially sectioned specimen the nerve divided at the epicondyle into its superficial radial and posterior interosseous divisions and all measurements were taken along it from that level. The nerve was sectioned by 18 cm. above the site of its terminal division. The branch pattern is shown in text fig. 2.

Superficial radial division.—Examination of the proximal 1·5 cm. of the superficial radial branch (extraneural) showed a constant pattern of three funiculi. The bundles containing the fibres of this branch occupied the anterior pole of the radial nerve from the site of its division to the 46 mm. level where one bundle fused with another of the posterior interosseous group. Over this length there were 23 changes in the superficial radial bundle pattern and the number of funiculi varied from 2 to 6 —the greatest length over which the pattern remained constant was 8 mm. Proximal to the 46 mm. level a partial exchange of fibres was gradually effected by anastomoses with neighbouring posterior interosseous and brachioradialis-radial extensor bundles. Despite these intercommunications the bulk of the cutaneous fibres remained concentrated about the anterior pole of the nerve in the furrow and about the deep aspect of its supero-lateral margin in the spiral groove. In these two regions, the remaining cutaneous fibres were scattered over the central portion of the nerve where they were associated principally with posterior interosseous fibres but partly also with other muscular fibres.

Posterior interosseous division.—The posterior interosseous division was composed of a single funiculus (which contained all the fibres for the muscles on the dorsum of the forearm) and five satellite supinator bundles for 3 mm. below its origin. The reduction of the posterior interosseous bundles to a single funiculus, which was observed in other specimens, prevented the study of the topography of the posterior interosseous branches within the radial trunk.

The fibres of two of the minute supinator bundles merged with those of the posterior interosseous at 10 and 14 mm. respectively. The

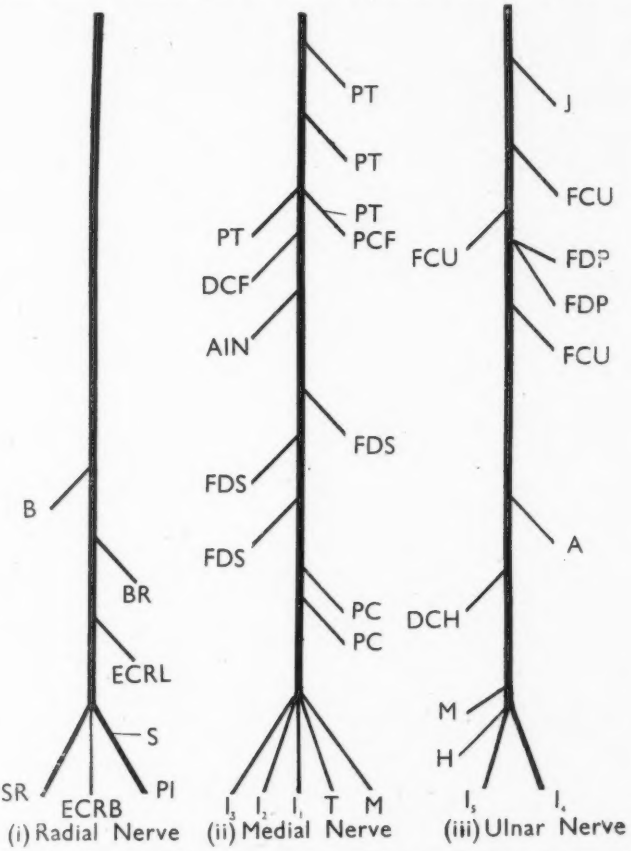

FIG. 2.—The branch pattern of the serially sectioned specimens of the left radial, median and ulnar nerves.

Radial nerve: SR = superficial radial; PI = posterior interosseous; S = supinator; ECRB and ECRL = extensor carpi radialis brevis and longus; BR = brachioradialis; B = brachialis.

Median nerve: I_1, I_2, I_3 = cutaneous branches to the first, second and third digital interspaces respectively; T = cutaneous branch to the radial side of the thumb; M = muscular branch; PC = palmar cutaneous; FDS = flexor digitorum sublimis; AIN = anterior interosseous branch; PCF and DCF = proximal and distal branches to the common flexor mass; PT = pronator teres.

Ulnar nerve: I_4, I_5, and H = cutaneous branches to the fourth digital interspace, ulnar side of the little finger and hypothenar eminence respectively; M = muscular or deep division; DCH = dorsal cutaneous of hand; FCU = flexor carpi ulnaris; FDP = flexor digitorum profundus; A = branch to the ulnar artery; J = branch to the elbow-joint.

three remaining bundles commenced to anastomose at 11 mm. and were collected into a single bundle at 30 mm.—in this process the large bundle originally located at the posterior pole moved to the medial surface in order to join the others.

At 35 mm. the supinator fibres, apart from a few scattered widely over the posterior interosseous group, were collected within and formed the bulk of one posterior interosseous funiculus. Above this level they were gradually disseminated over other funiculi in the group.

The posterior interosseous bundles were aligned as an independent system along the posterior pole of the nerve to the 46 mm. level where one fused with a superficial radial funiculus. 2 mm. further proximally some interosseous fibres passed to the radial extensor funiculus and above this level a further exchange of fibres was effected by anastomoses with neighbouring superficial radial and brachioradialis-radial extensor bundles. Despite this exchange the bulk of the posterior interosseous fibres continued to occupy the posterior pole and central portion of the nerve in the furrow and the infero-medial region as far as the brachio-axillary angle. The remaining fibres were scattered centrally in association principally with superficial radial fibres but partly with the brachioradialis-radial extensor elements.

The fibres of this branch remained more discretely localized in the nerve than those from the other branches, and even as far proximally as the brachio-axillary angle there were bundles which were composed solely of fibres from this division.

The distal 7 mm. of the posterior interosseous funicular pattern, excluding the independent supinator units, remained unchanged. Beyond this and as far as the level of the first fusion with a superficial radial bundle there were 45 changes in the pattern and the maximum length for which it remained constant was 2 to 3 mm.

Branch to extensor carpi radialis brevis.—This branch entered the deep aspect of the angle between the superficial radial and posterior interosseous divisions as a single funiculus which immediately migrated obliquely upwards and outwards, between the bundle groups representing those divisions, to reach the lateral aspect of the nerve 6 mm. above its point of entry. At 36 mm. it was joined by one of the two extensor carpi radialis longus funiculi and from this point proximally the brevis fibres were associated with those from that muscle.

Branch to extensor carpi radialis longus.—The number of bundles in the first 5 mm. of the extraneural portion of the branch to the extensor carpi radialis longus changed successively from 2 to 3 to 4 to 3. The

branch joined the nerve at 26 mm. as two bundles which were applied to its posterior pole against the posterior interosseous component. They were traced superficially beneath the posterior interosseous group and across the lateral surface of the nerve towards the extensor brevis bundle to the posterior aspect of which they were applied at 35 mm. One bundle fused with the extensor brevis funiculus at 36 mm. and the other anastomosed with this compound funiculus 2 mm. higher.

Compound funiculus containing the fibres for the extensores carpi radiales.—The funiculus formed by the fusion of the extensores carpi radiales bundles proceeded along the lateral surface of the nerve for 10 mm. when it received a small bundle from the posterior interosseous component and, 3 mm. more proximally, a contribution from the superficial radial component. 2 mm. higher, however, these newly added elements left and were probably accompanied by some of the extensor fibres.

At 63 mm. the extensor funiculus received the brachioradialis fibres and its subsequent fate will be discussed in the section devoted to the latter branch. Until this union the radial extensor bundle had not, apart from the brief and temporary presence of a few posterior interosseous and superficial radial fibres, contained representatives from any other branch. Both the longus and brevis fibres, however, had undergone a reorientation within the nerve prior to their fusion so that the compound funiculus containing them was located in a different quadrant from that of their site of entry.

Branch to brachioradialis.—The proximal 1·5 cm. of the branch to brachioradialis (extraneural) was composed of a constant pattern of three funiculi.

The branch entered the antero-lateral aspect of the nerve at 54 mm. and at 57 mm. the three funiculi were spread over the antero lateral aspect of the nerve anterior to the radial extensor fibres and lateral to those from the superficial radial branch. At 60 mm. the funiculi were reduced by fusion to 2; 3 mm. higher one of these anastomosed with the compound radial-extensor funiculus and 4 mm. further proximally the other did likewise.

At higher levels the funiculus containing the brachioradialis-radial extensor fibres repeatedly divided and anastomosed with adjacent bundles. These intercommunications resulted first in the local dissemination of its contained fibres and subsequently in a more general scattering. However, though they were ultimately dispersed over many funiculi the bulk of the fibres remained concentrated first about the anterior pole (furrow)

and finally in the lateral quadrants of the nerve as far as the brachio-axillary angle.

Branch to brachialis.—Between its origin and the site of its entry into the muscle the branch to brachialis was composed of a single funiculus.

At 71 mm. the funiculus entered the anterior pole of the nerve between the superficial radial and brachioradialis-extensor fibres which were medial and postero-lateral to it respectively. The funiculus then moved posteriorly between the two bundle systems and at 78 mm. fused with the antero-medial surface of the brachioradiali-extensor funiculus which, at this level, had already discarded some of the extensor fibres. Above this level the brachialis fibres participated in the changes recorded for the brachioradialis-extensor funiculis.

Branches to the triceps and the posterior cutaneous nerve of the forearm.—In all the dissected specimens (20) the branch or branches to the long head arose in the axilla or brachio-axillary angle and ran an independent course along the medial margin of the radial nerve to its destination.

The branches to the medial and lateral heads of triceps and the posterior cutaneous nerve of the forearm commonly separate from the main trunk in the brachio-axillary angle or at the entrance to the spiral groove and accompany the nerve in the same loose sheath for some distance along the groove before finally leaving to pass to their destination. This was the arrangement obtaining in the specimens dissected and also in those examined microscopically where the bundle systems for each branch remained quite distinct as far as the brachio-axillary angle beyond which they were not traced. In the spiral groove the branches to the lateral and medial heads coursed along the supero-lateral and infero-medial aspects of the superficial or posterior surface of the nerve respectively. The posterior cutaneous nerve of the forearm was usually aligned along the supero-lateral margin but occasionally coursed along the infero-medial margin.

Summary.

(1) *Intraneural topography of the branches of the radial nerve.*—There was a discrete funicular localization of the branches in approximately the distal 7 cm. of the nerve. Over this length the variations in the funicular pattern were due predominantly to intercommunications occurring within, but not between, bundle groups, each of which represented a branch. Intercommunications between groups occurred over the more proximal portion of this length but, though resulting in some intermingling of fibres, did not significantly disturb the intraneural localization which was as follows:

0 to 26 mm.	
Anterior:	Superficial radial
Posterior:	Posterior interosseous
	Supinator
Lateral:	Extensor carpi radialis brevis
Medial:	Supinator
26 to 29 mm.	
Anterior:	Superficial radial
Posterior:	Posterior interosseous
	Extensor carpi radialis longus
Lateral:	Extensor carpi radialis brevis
Medial:	Supinator
29 to 52 mm.	
Anterior:	Superficial radial
Posterior:	Posterior interosseous
Lateral:	Extensor carpi radialis longus
	Extensor carpi radialis brevis
Medial:	Supinator
52 to 70 mm.	
Anterior and/or antero-medial:	Superficial radial
Anterior and/or antero-lateral:	Brachioradialis
Posterior:	Posterior interosseous
Lateral:	Extensores carpi radiales
Medial:	Posterior interosseous
	Supinator

At more proximal levels the funicular divisions and intercommunications increased the intermixture of fibres which was, in the first instance, local and not general. This meant that some funiculi remained which contained fibres from the same source while others contained fibres from a variety of sources. At higher levels the dispersal of fibres became progressively more widespread but, despite this, fibres from individual branches remained relatively concentrated within certain quadrants of the nerve. The degree of localization obtaining under these circumstances was far less than that observed at distal levels but the findings suggested that it was sufficiently pronounced to be significant. The localization above the distal 7 cm. of the nerve was as follows:

In the intermuscular furrow:

Anterior:	Brachialis
Antero-lateral and/or lateral:	Brachioradialis
	Extensores carpi radiales
Anterior and/or antero-medial:	Superficial radial
Central:	Superficial radial
	Posterior interosseous
Posterior and postero-medial:	Posterior interosseous

In the spiral groove and brachio-axillary angle the fibre concentration was as follows:

Supero-lateral—	
Posterior (superficial):	Posterior cutaneous of forearm
	Lateral head of triceps
	Extensores carpi radiales
	Brachioradialis
	Brachialis
Anterior (deep):	Superficial radial
Infero-medial—	
Posterior (superficial):	Medial head of triceps
	Posterior interosseous
Anterior (deep):	Posterior interosseous

For purposes of comparison the localization reported by previous investigators is shown in Table I.

TABLE I.—INTRANEURAL TOPOGRAPHY OF THE RADIAL NERVE.

Branch	*Stoffel*	*Marie, Meige and Gosset*	*Dejerines and Mouzon*	*Kraus and Ingham*
Brachio-radialis	Lateral	Lateral	Lateral	Lateral
Extensores carpi radiales	Postero-lateral	Medial	Postero-lateral	Anterior in some and posterior in others. Discrepancy attributed to torsion of the nerve
Posterior interos-seous group	Supinator: medial Remainder: postero-medial	Extensors of the fingers: postero-medial	Medial — arranged from anterior to posterior: Ext. carpi ulnaris Thenar Ext. dig. comm. Supinator	Ext. indicis proprius: medial
Superficial radial	Anterior			

(2) *The length of branches as separate and independent bundle groups within the nerve.*—The lengths, which are given below, for which individual branches coursed as separate and independent bundle groups (though with varying pattern) within the nerve are a measure of the extent to which the branches may be safely stripped without damaging or interfering with the fibre-architecture of the nerve.

Posterior interosseous	46 mm.
Superficial radial	46 mm.

From the nature of the exchanges occurring between these two bundle groups it would appear that their separation for a further 26 mm. would involve only a negligible proportion of the fibres of each component.

Extensor carpi radialis brevis:		
(*a*) Separate		36 mm.
(*b*) In common radial extensor funiculus		10 mm.
Extensor carpi radialis longus:		
(*a*) Separate	Funiculus (i)	10 mm.
	Funiculus (ii)	12 mm.
(*b*) In common radial extensor funiculus		10 mm.
Brachioradialis	(i)	9 mm.
	(ii)	13 mm.
Brachialis		7 mm.

(3) *The constancy of the funicular pattern.*—The greatest length over which the entire funicular pattern remained constant was the distal 7 mm. of the nerve though in this segment there were a few very minor changes in the pattern of the superficial radial component and an alteration in the position of the extensor carpi radialis brevis funiculus. Proximal to this the greatest length over which the entire pattern remained constant was 4 mm. though individual funiculi pursued longer courses before anastomosing or dividing.

Median Nerve.

At the wrist the flattened nerve has anterior and posterior surfaces with radial and ulnar margins. Between the wrist and the pronator teres it is oval to round in outline with anterior and posterior surfaces and radial and ulnar poles. In the cubital fossa the flattened nerve is so aligned that the anterior and posterior surfaces are now directed medially and laterally respectively thus making the radial and ulnar poles the anterior and posterior margins respectively. In the upper arm it is applied against the brachial artery and has lateral, deep or muscular, and medial, superficial or subcutaneous surfaces with anterior and posterior margins.

In the serially sectioned specimen the nerve divided into its cutaneous and thenar muscular branches 37 mm. below the radial styloid line. All measurements along the nerve were made, in millimetres, from the site of its division but the level of any described feature of the pattern can be calculated with reference to the styloid line, which crossed the nerve at 37 mm., and the humeral epicondylar line, which crossed it at 297 mm. The nerve was sectioned for a further 103 mm. above the latter level. The branch pattern is shown in text fig. 2.

The fate of the Funiculi Comprising the Terminal Branches of the Median Nerve.

Muscular.

(*a*) *Thenar group.*—The thenar muscles were innervated by a large branch composed of one large funiculus and a smaller branch containing two bundles.

(i) Large muscular branch: The single funiculus joined and proceeded along the mid-anterior surface of the nerve for 45 mm. before inclining sharply towards the radial margin around which it curved to reach the postero-radial aspect at 56 mm. where a small bundle of fibres left and passed to the funiculus devoted to the cutaneous fibres from the radial aspect of the thumb. In its course it ascended for 45 mm. on the ulnar side of the cutaneous funiculus from the radial aspect of the thumb, then anterior to it for 4 mm. and finally on its radial side. Proximal to the 56 mm. level the muscular fibres were gradually dispersed over neighbouring funiculi until at 75 mm. they were, together with the cutaneous fibres from the thumb and first interspace, scattered over all the funiculi occupying the radial quadrants. Above this level further intercommunications carried the muscular fibres ulnarwards until at 100 mm. they were widely distributed over every funiculus except those containing the cutaneous fibres from the second and third interspaces and from the palm which were arranged anteriorly and on their radial side respectively. It was not until 234 mm. that all funiculi, with the exception of the recently added anterior interosseous bundles, contained fibres of the thenar muscular branch.

(ii) Small muscular branch: The two bundles were traced into the nerve behind and to the radial side of the large muscular funiculus. At 5 mm. they fused and then wound round the ulnar margin of the large muscular funiculus to reach, at 8 mm. the anterior surface between the latter and the second lumbrical funiculus. At 17 mm. the bundle split into two and one received the funiculus of the second lumbrical muscle. At 50 mm. both bundles occupied the anterior surface towards the centre and that containing the second lumbrical fibres fused with a cutaneous funiculus from the first interspace. After a further 4 mm. the second bundle fused with that funiculus from the first interspace which contained the first lumbrical fibres. At higher levels the fibres were gradually disseminated over the remaining funiculi though the bundle containing the first lumbrical fibres remained separate for a further 6 mm.

In their course the small thenar muscular and lumbrical fibres moved to the radial margin and then round it to the dorsum of the nerve where they were still confined to the postero-radial quadrant at 110 mm. Above this level they were more widely diffused through the nerve.

(*b*) *First and second lumbrical fibres.*—The fibres from the first lumbrical muscle entered the cutaneous branch from the first interspace. Within this branch they were always confined to a single funiculus to

which other bundles were added but which never itself divided. At 54 mm. the funiculus carrying these fibres fused with one of the small muscular thenar group—the behaviour of the former above this level has already been described in that section of the text devoted to the muscular fibres.

The single funiculus from the second lumbrical entered the anterior surface, to the posterior and ulnar side of the large thenar muscular bundle, and continued proximally for 17 mm. before anastomosing with one of the small muscular thenar group.

CUTANEOUS.

Digital branch from the third interspace.—The bundle group containing the digital cutaneous fibres from the third interspace pursued the longest intraneural course of any terminal branch intermingling with fibres from another source.

The bundles were clumped about the ulnar margin of the nerve for 54 mm., and were arranged as a layer over the antero-ulnar surface for a further 12 mm. before one anastomosed with another from the digital branch of the second interspace. 4 mm. higher further communications occurred between these bundle groups. At 81 mm. all third interspace bundles contained fibres from the second interspace though they themselves had not altered their relative position in the nerve. The process to date therefore represented an assimilation of the second interspace cutaneous fibres.

Between 86 and 95 mm. the bundles, now carrying second and third space fibres, gradually spread across the anterior surface and were still arranged anteriorly at 106 mm. At this level one anastomosed with a small bundle containing cutaneous fibres from the thumb and first interspace and terminal muscular fibres. Above this level the fibres from the second and third spaces remained discretely localized anteriorly or antero-radially. At 160 mm. they were collected into a single bundle for 2 mm. on the antero-radial aspect of the nerve.

Between 179 and 223 mm. further intercommunications with bundles containing cutaneous and flexor digitorum sublimis fibres were observed. Those from the second and third spaces, however, remained concentrated in the antero-radial, and later anterio, quadrants until the 224 mm. level when the bundles containing them commenced to undergo more extensive and complicated anastomoses with neighbouring funiculi. Despite these exchanges most of the third space fibres were confined to the centro-medial

segment at 254 mm. Above this level they were more widely scattered so that at 290 mm. the fibres were represented in all the funiculi with the exception of the pronator teres, anterior interosseous and common flexor bundles, and one funiculus containing fibres of all the remaining branches. At 375 mm. they were contained in every funiculus with the exception of that from the proximal branch to the pronator teres.

Digital branch from the second interspace.—The digital cutaneous fibres from the second interspace joined and proceeded along the postero-ulnar and central portion of the nerve for 58 mm. at which level one bundle fused with a neighbouring bundle from the first interspace. Between 68 and 97 mm. intercommunications occurred with funiculi of which some contained cutaneous fibres from the third space and others, cutaneous fibres from the first space and muscular fibres. The highest level at which a bundle was composed solely of second space fibres was 97 mm. At 128 mm. these cutaneous fibres were widely distributed over the funiculi which occupied all but the dorsal surface though the bulk of them appeared to be contained in the third space bundles on the anterior surface. Proximal to this they became progressively dispersed over the remaining bundles.

Digital branch from the first interspace.—The bundle group containing the digital cutaneous fibres from the first interspace, and one bundle composed of muscular fibres from the first lumbrical, entered the radial margin just deep to the funiculus from the radial side of the thumb and ascended in this position for 50 mm. At this level a few bundles had reached a more central position and one fused with another carrying muscular fibres from the thenar and second lumbrical muscles. Further proximally the fibres were disseminated over neighbouring funiculi until at 95 mm. they were widely distributed over the posterior three-fourths of the nerve and the bundles anterior to them contained only fibres from the second and third spaces. It was not until the 225 mm. level that all funiculi, with the exception of those from the anterior interosseous branch, contained cutaneous fibres from the first space.

Cutaneous branch from the radial aspect of the thumb.—The single bundle of the cutaneous branch from the radial aspect of the thumb entered and continued along the antero-radial quadrant of the nerve for 56 mm. before receiving a small bundle of muscular fibres from the thenar group. At 59 mm. the single funiculus divided and from this point onwards engaged in plexus formations with neighbouring bundles, par-

ticularly those representing the thenar muscles and first interspace. The subsequent course of these fibres has been covered in previous sections.

General.—The bundle groups representing the terminal branches remained quite separate over the distal 50 mm. of the nerve except for one anastomosis at 17 mm. between a small bundle carrying the second lumbrical fibres and another from the thenar muscles. Over this distance the bundle pattern in each case underwent frequent changes while extensive migrations of bundle groups and individual bundles were also observed—particularly at about the 50 mm. level where they were induced by the twist imparted to the nerve as it turned round the flexor digitorum sublimis.

Though the muscular fibres were soon dispersed over the neighbouring cutaneous funiculi from the thumb and first space they nevertheless retained some measure of localization at the radial margin and later over the dorsum of the nerve.

The cutaneous bundles from the thumb and first space anastomosed soon after the addition of muscular fibres to the former. Those from the second and third spaces were the last to interlace and the compound bundles outlined by their fusion and division remained well localized for some distance over the anterior surface and antero-radial portion of the nerve before intercommunicating with the remaining compound bundles representing the other terminal branches.

Above the entrance of the anterior interosseous and distal common flexor branches bundles containing the terminal fibres occupied the anterior three-fifths of the nerve. With the entrance of the proximal common flexor bundles anterior to them they became centrally situated. Continuing proximally they were arranged about the central axis of the nerve and anastomosed among themselves and with adjacent funiculi containing common flexor and anterior interosseous fibres. Above 303 mm. an occasional bundle containing terminal branch fibres reached the anterior and posterior margins of the nerve. In the medial root they were concentrated postero-medially but at 400 mm. were widely scattered over the three bundles present at that level. In the lateral root they were widely distributed centrally and at 400 mm. were contained in every funiculus with the exception of one devoted entirely to pronator teres fibres.

The number of changes of pattern in the individual terminal cutaneous and muscular bundle systems prior to their initial fusion and the longest section with a constant pattern in each case was as follows:

	Level of initial fusion	*Changes*	*Maximum length with constant pattern*
Cutaneous branches			
Third space	66 mm.	43	5 mm.
Second space	58 mm.	18	9 mm.
First space	50 mm.	18	5 mm.
Radial aspect thumb	56 mm.	6	45 mm.
Muscular branches			
Large thenar	56 mm.	0	56 mm.
Small thenar	17 mm.	2	6 mm.
Second lumbrical	17 mm.	0	17 mm.

Palmar Cutaneous Branches.

There were two palmar cutaneous branches each of which was composed of a single funiculus. The more distal joined the antero-radial aspect of the nerve at 55 mm. The more proximal joined the postero-radial aspect of the nerve at 92 mm. and ascended towards the distal branch which it reached at 105 mm. and with which it fused at 116 mm.

The common bundle proceeded along the radial margin and at 129 mm. temporarily joined a bundle containing cutaneous fibres from the second and third interspaces. It left 3 mm. further proximally without any exchange of fibres and proceeded along the radial margin to the 154 mm. level where it joined a bundle containing terminal cutaneous and muscular fibres. The palmar cutaneous fibres continued in this bundle for 36 mm. and were then gradually scattered over neighbouring bundles. Despite this dispersal they remained relatively localized in the radial, and later anterior, quadrants as high as 275 mm. above which they were more widely diffused. A few of these fibres entered the lateral root of the nerve but the majority appeared to enter the medial.

Branches to the Flexor Digitorum Sublimis.

There were three separate branches to the flexor digitorum sublimis:

(1) The two funiculi comprising the distal branch entered the ulnar margin of the nerve at 109 mm. and, after a course of 2 mm. and 4 mm. respectively, joined the same compound terminal cutaneous funiculus. The sublimis fibres were subsequently shared with another neighbouring bundle and at 132 mm. the bundle of the intermediate branch became associated with the system. As far as this level the distal sublimis fibres were confined to the antero-ulnar quadrant.

(2) The single funiculus of the intermediate branch entered the ulnar aspect of the nerve at 129 mm. and, at 132 mm., fused with one of the funiculi containing fibres of the distal branch. Further anastomoses and

divisions of the bundles containing the sublimis fibres gradually resulted in their distribution over neighbouring funiculi though they remained relatively localized in the antero-ulnar quadrant in the forearm. This position was retained until they were joined by the fibres of the proximal branch.

(3) The proximal branch of two funiculi entered the antero-radial aspect of the nerve at 191 mm. The funiculus outlined by their union at 195 mm. continued obliquely upwards across the anterior surface towards the ulnar margin of the nerve about which were scattered the sublimis fibres which had been added at more distal levels. At 200 mm. it had reached the middle of the anterior surface and 12 mm. higher the ulnar margin of the nerve. At 207 mm. a small bundle separated from its deep surface and, after an independent course of 6 mm., fused with a neighbouring bundle containing, amongst others, sublimis fibres. This process was repeated at 215 mm. while the remainder of the funiculus continued for 4 mm. before dividing into two bundles. One of these, at 223 mm., fused with a neighbouring bundle carrying sublimis fibres in addition to those from other sources while 1 mm. higher the second joined an adjacent bundle containing cutaneous fibres from the second and third interspaces. As far as the cubital fossa the sublimis fibres were contained in the ulnar quadrants. Above this, and despite further intercommunications, they remained concentrated in the centro-medial segment of the nerve as far proximally as 240 mm. The extent of the scattering then increased until ultimately (267 mm.) the fibres were distributed over most of the funiculi which occupied the central and medial portion of the nerve but were not present in the recently-added anterior interosseous, common flexor and pronator teres bundles. At 340 mm. they were widely distributed over all but a few funiculi.

Anterior Interosseous Branch.

An anterior interosseous branch entered the ulnar margin of the nerve at 224 mm. as a group of five funiculi. This bundle group was concentrated in turn along the ulnar, then posterior, margin and postero-lateral angle for 84 mm. 51 mm. above the site of entry a small bundle joined a neighbouring funiculus, containing an admixture of terminal and flexor sublimis fibres, as a result of which a few interosseous fibres were carried anteriorly.

Proximal to 307 mm. the dispersal of the anterior interosseous fibres was effected by the division of their funiculi together with intercommunications with adjacent bundles containing, on the one hand, common flexor

fibres and, on the other, representatives of all the more distal branches. At 312 mm. the anterior interosseous bundles were arranged over the postero-lateral quadrant but 5 mm. further proximally they were again concentrated for 10 mm. at the postero-lateral angle. They were then carried forwards across the lateral surface over which, at 341 mm., they were widely dispersed though the bulk of them was situated posteriorly. They retained this position until they entered the medial and lateral roots of the nerve—most of the fibres accompanied the former division. At 375 mm. the fibres destined for the medial root were collected into one funiculus and those destined for the lateral root were contained in two. At 400 mm. the fibres in the lateral root were situated centrally in three funiculi while those in the medial root were contained in all three bundles present at that level.

There were 16 changes in the funicular pattern of this branch prior to its contributing a small bundle at 275 mm. to a funiculus bearing fibres from another source. The longest section with a constant pattern was 7 mm. There were only four changes in the pattern between 275 and 307 mm. but at the latter level further and more extensive intercommunications occurred with neighbouring bundles. The longest section without a change above 275 mm. was 18 mm.

Branches to the Common Flexor Mass.

Two branches supplied the common flexor mass. The more proximal gave twigs to the pronator teres and the flexor carpi radialis while the distal supplied the flexor digitorum sublimis and some fibres to the flexor carpi radialis.

Distal branch.—The two funiculi of the distal branch, which fused within 1 mm. of entering the nerve, joined the posterior margin at 245 mm. where they were applied against the anterior interosseous bundles. The fibres proceeded along the posterior margin and finally entered the medial root. At 375 mm. they were still concentrated posteriorly but at 400 mm. were contained in all funiculi of the medial root. At 313 mm. the bundle carrying them anastomosed with one carrying representatives of all the more distal branches but, though the funiculi containing the common flexor fibres subsequently participated in further plexus formations, the fibres remained discretely localized at the posterior pole. Between the 278 and 281 mm. levels they were arranged in two bundles but elsewhere, and until intercommunications occurred with other bundle systems, they were gathered into a single bundle.

Proximal branch.—The four bundles of the proximal branch entered

the anterior margin of the nerve at 255 mm. The only anastomoses occurring along the course of this bundle group were with bundles from the distal and intermediate branches of the pronator teres at 260 and 280 mm. respectively and with another bundle, at 360 mm., containing distal fibres with the exception of those from the anterior interosseous and distal common flexor branches. The fibres were compactly arranged along the anterior pole for 62 mm. and then, as a single bundle, ascended obliquely for a further 14 mm. to the mid-line of the medial surface. The bundle then sank into the nerve and at 335 mm. was rather deeply placed on the line of union of the medial and lateral roots of the nerve. This position was retained until a separation occurred between the bundles comprising the two roots. Those carrying the proximal common flexor and pronator teres fibres then accompanied the posterior margin of the lateral root where they were concentrated in two funiculi at 400 mm.

The proximal common flexor fibres were confined to a single bundle over the following segments: 264 to 266 mm., 294 to 304 mm., 315 to 342 mm. and 360 to 372 mm. In the intermediate segments the number of bundles containing them did not exceed four and the fibres were usually contained in two.

The proximal branch showed a constant pattern for the first 5 mm. of its intraneural course and then received a few pronator fibres. No further anastomoses occurred for 22 mm. over which length there were eight changes of pattern. The longest section with a constant pattern was 9 mm.

Branches to Pronator Teres.

There were three separate branches to the pronator teres.

The distal branch joined the medial surface of the nerve at 255 mm. and ascended obliquely upwards and forwards across it to unite, at 260 mm., with that bundle in the proximal common flexor group which had come from the pronator teres.

The intermediate branch joined the postero-medial aspect of the nerve at 270 mm. and, as it ascended, migrated forwards across the medial surface to reach and fuse at 282 mm. with a proximal common flexor bundle containing pronator teres fibres. From this point onwards the fibres were incorporated in the proximal common flexor group with which they have been described.

The proximal branch entered the anterior margin of the nerve at 302 mm. as three bundles and these were reduced to one after an intraneural course of 6 mm. This funiculus, apart from temporary divisions into two or three, coursed proximally along the anterior margin

and entered the lateral root of the nerve without anastomosing. At 400 mm. the bundle was still situated at the anterior margin of the lateral root.

SUMMARY.

(1) *Intraneural topography of the branches of the median nerve.*—The bundle groups representing the terminal branches remained separate over the distal 50 mm. of the nerve except for an anastomosis at 17 mm. between a small bundle carrying the second lumbrical fibres and another from the thenar muscles. Over this length each individual bundle group underwent frequent changes of pattern while extensive intraneural migrations of individual bundles were also observed.

Of the branches added in the region of the elbow, several pursued independent courses for considerable distances before participating in plexus formations with adjacent bundle groups.

As the nerve ascended the scattering and intermingling of terminal branch fibres gradually terminated their localization. The branches given off about the elbow, on the other hand, remained sharply localized for considerable distances in the upper arm.

The intraneural shift of bundles and entire bundle systems was more extensive than that observed in either the radial or ulnar nerves and was a conspicuous feature of the pattern. Such migrations were responsible for the same bundle system occupying different quadrants of the nerve at different levels thereby rendering impossible any simplified account of the localization obtaining along the nerves. The following varieties of intraneural shift were observed:

(i) The change induced by the twist imparted to the nerve as it turned round the flexor digitorum sublimis just above the wrist.

(ii) The migration of branch bundles to reach fibres from the same source when these were situated some distance from the site of entry of the new branch. This is well illustrated by the flexor digitorum sublimis fibres, the proximal branch of which moved across the anterior face of the nerve to reach the region occupied by sublimis fibres which had entered at more distal levels.

(iii) Migrations which were apparently undertaken in order that fibres should reach the appropriate division or root of the nerve.

(iv) Migrations occurring for no apparent reason as for example when the bundle bearing proximal common flexor and pronator teres fibres moved from the anterior pole across the medial surface of the nerve in order to reach a central position.

The following localization obtained in the serially-sectioned specimen. Reference to the accompanying diagrams will indicate the exact nature and extent of the localization.

0 to 54 mm.

Ulnar segment:	Third interspace
Central segment:	Posterior: Second interspace Anterior: Small thenar muscular Second lumbrical Few first interspace from 42 mm.
Radial segment:	Posterior: First interspace Anterior: Large thenar muscular and fibres from radial aspect of thumb. The former bundle passed anteriorly from the ulnar to the radial side of the cutaneous bundle.

54 to 81 mm.

Postero-radial:	Large thenar muscular First interspace	
Antero-radial:	Radial aspect of thumb First interspace (few) Small thenar muscular Lumbrical	Intermingle from 60 mm. onwards
	Palmar cutaneous	
Postero-ulnar:	Second interspace	
Antero-ulnar:	Second (few) and third interspace	

81 to 109 mm.

Ulnar margin:	Second interspace
Radial margin:	Palmar cutaneous
Antero-ulnar moving to anterior:	Third and second interspace
Antero-radial and/or posterior quadrants:	Combined muscular fibres and cutaneous fibres from the first interspace and the radial aspect of the thumb

109 to 191 mm.

Ulnar margin and antero-ulnar quadrant:	Flexor digitorum sublimis
Radial margin and postero-radial quadrant:	Palmar cutaneous
Anterior moving to antero-radial:	Second and third interspace—the latter were concentrated to the radial side of the former.
Postero-radial and ulnar quadrants:	Terminal muscular fibres and cutaneous fibres from the radial aspect of thumb and first interspace

191 to 202 mm.

The fibre concentration was as follows:

Ulnar quadrants:	Flexor digitorum sublimis
Radial pole:	Palmar cutaneous
Antero-radial:	Second and third interspace
Radial margin proceeding across the anterior surface to the ulnar margin:	Proximal branch to flexor digitorum sublimis

202 to 220 mm.

The fibre concentration was as follows:

Ulnar quadrants:	Flexor digitorum sublimis
Anteriorly:	Second and third interspace
Radial edge:	Palmar cutaneous

220 to 245 mm.

The anterior interosseous bundles were situated at the ulnar and later posterior pole of the nerve from 224 mm. The fibres of the terminal branches were mixed and widely dispersed. The flexor digitorum sublimis and third interspace fibres were concentrated medially (the former posterior to the latter) and the palmar cutaneous fibres anteriorly.

245 to 273 mm.

The fibres were arranged in individual groups from posterior to anterior as follows: —

(1) Distal common flexor fibres.
(2) Anterior interosseous fibres.
(3) Combined fibres from branches distal to the above with some concentration of the flexor digitorum sublimis and third interspace fibres medially and of the palmar cutaneous fibres anteriorly.
(4) Proximal common flexor at anterior pole above 255 mm.

Between 255 and 260 mm. a pronator teres bundle moved over the medial surface towards the anterior pole.

273 to 308 mm.

Anterior pole:	Medial: Pronator teres Lateral: Proximal common flexor
Central:	Terminal, palmar cutaneous and flexor digitorum sublimis fibres
Posterior pole:	Medial: Distal common flexor Lateral: Anterior interosseous
Medial surface:	Pronator teres ascending from the posterior to the anterior pole which it reached at 278 mm.

308 to 375 mm.

Anterior pole:	Pronator teres
Antero-medial:	Proximal common flexor Pronator teres Terminal, palmar cutaneous and flexor digitorum sublimis above 336 mm.
Antero-lateral:	Terminal, palmar cutaneous and flexor digitorum sublimis fibres and few anterior interosseous

Central and postero-medial:	Terminal, palmar cutaneous and flexor digitorum sublimis fibres
Postero-lateral:	Anterior interosseous
Posterior pole:	Distal common flexor medially Anterior interosseous laterally

375 to 400 mm.

Medial root:	Distal common flexor at posterior pole Anterior interosseous—postero-lateral Terminal, palmar cutaneous and flexor digitorum sublimis fibres spread over the remaining area

All traces of localization lost above 384 mm.

Lateral root:	Anterior: Pronator teres Lateral and central: Anterior interosseous and terminal, palmar cutaneous and flexor digitorum sublimis fibres Posterior: Proximal common flexor and pronator teres

For purposes of comparison the localization reported by previous investigators is shown in Table II.

TABLE II.—INTRANEURAL TOPOGRAPHY OF THE MEDIAN NERVE (UPPER ARM).

Branch	*Stoffel*	*Marie, Meige and Gosset*	*Kraus and Ingham*
Pronator teres	Lateral	Antero-lateral	Cross anteriorly from lateral to medial as they descend
Flexor carpi radialis	Lateral	Medial and lateral	Antero-medial
Flexor dig. sublimis	Medial	Postero-medial	Antero-medial
Flexor dig. profundus	Postero-medial	Postero-medial	Antero-medial
Flexor pollicis longus	Postero-medial	—	Anterior to antero-medial
Palmaris longus	Lateral	—	Anterior
Pronator quadratus	Postero-medial	Antero-lateral	Lateral and postero-lateral
Thenar	Anterior	Posterior	Mid-forearm level Abductor pollicis brevis: lateral Opponens: postero-medial
Lumbricals	—	—	Mid-forearm level. Postero-lateral
Cutaneous	Anterior	—	Mid-forearm level. Anterior

(2) *The length of branches as separate and independent bundle systems within the nerve.*—The following were the lengths for which the branches could be safely stripped without damaging or interfering with the fibre architecture of the nerve.

Terminal branches:	
Muscular:	
Large thenar	56 mm.
Small thenar	17 mm.
Second lumbrical	17 mm.
Cutaneous:	
Third interspace	66 mm.
Second interspace	58 mm.
Combined third and some second interspaces	0 to 106 mm.
First interspace	50 mm.
Radial aspect of thumb	56 mm.
Combined muscular and cutaneous	110 mm
Further separation of this group jeopardizes fibres to the flexor digitorum sublimis and in particular those to the index finger.	
Palmar cutaneous branches:	
Distal branch	61 mm.
Proximal branch	24 mm.
Combined branches	13 mm.
Flexor digitorum sublimis branches:	
Distal branch	2 to 4 mm.
Intermediate branch	3 mm.
Proximal branch	22 mm.
Anterior interosseous branch	51 mm
Common flexor branches:	
Distal branch	68 mm.
Proximal branch	5 mm.
Proximal branch plus some pronator teres fibres	105 mm.
Pronator teres branches:	
Distal branch	5 mm.
Distal branch plus proximal common flexor	105 mm.
Intermediate branch	12 mm.
Intermediate branch plus proximal common flexor	78 mm
Proximal branch	98+mm.

(3) *The constancy of the funicular pattern.*—Below the epicondyle there were 335 changes in the pattern and the longest section for which it was constant was 5 mm. Between the epicondyle and the site of division of the nerve into its medial and lateral heads there were 93 changes of pattern and the longest section for which it was constant was 3 mm. In the remaining 37 mm. of the nerve the lateral root showed 18 changes of pattern with a maximum constant length of 7 mm. while the corresponding values for the medial root were 42 and 3 respectively.

Ulnar Nerve.

In the distal three-fourths of the forearm the nerve is flattened or oval in outline and has anterior and posterior surfaces with radial and ulnar margins. In the upper-fourth it lies in an interval outlined between the flexor carpi ulnaris, flexor digitorum sublimis and flexor digitorum pro-

fundus muscles and there presents deep, lateral or radial and superficial, medial or ulnar surfaces with anterior and posterior margins. In the epicondylar groove the nerve has margins directed towards the tip of the epicondyle medially and the olecranon and trochlea fossa laterally while the surfaces are posterior, superficial or subcutaneous, and anterior, deep, or bony. Above the epicondyle the nerve is oval in outline and presents superficial, subcutaneous or medial, and deep, muscular or lateral surfaces with anterior and posterior margins.

In the described serially sectioned specimen the nerve divided into its superficial and deep terminal branches 20 mm. below the radial styloid line. All measurements along the nerve were made, in millimetres, from the site of its division but any described feature of the pattern can be calculated with reference to the styloid line, which crossed the nerve at 20 mm., and the humeral epicondylar line, which crossed it at 280 mm. The nerve was sectioned for a further 130 mm. above the latter level. The branch pattern is shown in text fig 2.

The Fate of the Funiculi Comprising the Terminal Branches of the Ulnar Nerve at the Wrist.

(1) *The deep muscular division.*—The funiculus to the abductor digiti quinti, which branched from the deep division before it passed deeply, joined one of the bundles of the latter at 50 mm. The muscular fibres then proceeded as a separate bundle group for a further 40 mm. when a small bundle joined a neighbouring cutaneous funiculus while at 95 mm. they were joined by some cutaneous fibres. Further intercommunications between the terminal deep and superficial bundle systems were observed but, as high as 115 mm., the exchanges had involved only immediately adjacent bundles. The anastomoses and divisions then became more frequent and complicated so that at the 140 mm. level fibres of both divisions were contained in all the funiculi with the exception of those representing recently added branches.

The deep division joined and curved around the postero-ulnar aspect of the nerve to gain its extreme ulnar margin. The funiculi were arranged to the ulnar side of those from the superficial division as far proximally as their fusion with them. They occupied the ulnar quadrants until the entry of the dorsal cutaneous branch bundles on their ulnar side. Above this they were more centrally situated. Anastomoses between the funiculi of the deep and superficial divisions scattered the muscular fibres through the nerve towards the radial margin but despite this they remained relatively concentrated centrally till the 120 mm. level. At

140 mm. the three funiculi bearing both cutaneous and muscular fibres occupied the central and radial portions of the nerve with the dorsal cutaneous bundles to their ulnar side.

There were 22 changes in the funicular pattern of the deep division prior to its initial fusion with the superficial system at 90 mm. The number of funiculi varied from one to five—usually there were one or two large funiculi with or without one to three small satellites. The longest section with a constant pattern was 18 mm.

(2) *The superficial cutaneous division.*—Unlike the deep division, the superficial was composed of numerous small funiculi with only an occasional large one.

The funiculi of the three cutaneous branches proceeded as separate bundle groups for 48 mm. when a small bundle from the fourth interspace fused with one from the ulnar side of the little finger. At 52 mm. one of two funiculi from the hypothenar region joined one of the group from the ulnar side of the little finger and at 75 mm. each funiculus of the cutaneous group contained fibres from each of the terminal cutaneous branches. The palmaris brevis fibres which were contained in this system could not be identified.

The funiculi of the three cutaneous branches occupied the radial quadrants of the nerve. Until their fibres intermingled, those from the hypothenar region, the ulnar side of the little finger and the fourth interspace were arranged in that order from before backwards.

Despite intercommunications with the muscular bundles the cutaneous fibres remained relatively concentrated in the radial and later anteroradial quadrants till the 120 mm. level.

The number of changes of pattern in the individual cutaneous bundle groups prior to their initial fusion, which occurred between 48 and 52 mm., and the longest section with a constant pattern in each case were as follows:

Hypothenar eminence	10	12 mm.
Ulnar side of little finger	19	5 mm.
Digital to the fourth interspace	10	7 mm.

Prior to the anastomosis of the muscular and combined cutaneous bundles at 90 mm. there were 36 changes of pattern in the 42 mm. length of the latter and the longest section with a constant pattern was 5 mm.

Over the distal 90 mm. of the nerve there were 75 and 22 changes in the pattern of the cutaneous and muscular bundle groups respectively. Despite the numerical preponderance of cutaneous fibres, the difference is probably an expression of the greater complexity of sensory mechanisms

as opposed to motor and reflects the need, in the case of cutaneous branches, for frequent and more complicated anastomoses in order to effect the requisite sorting and combining of sensory fibres before reaching the unit area they are to innervate.

Funiculi containing both muscular and cutaneous fibres.—Anastomoses between the funiculi of the superficial and deep divisions commenced at 90 mm. and 50 mm. further proximally all bundles contained fibres from both.

From 140 to 143 mm. the muscular and cutaneous fibres were collected into three bundles. These were reduced to a single bundle between 153 and 155 mm.—above and below this segment the number of funiculi varied considerably.

No other fibres were added to the group until 251 and 252 mm. when it was joined by some dorsal cutaneous and arterial fibres respectively. At higher levels fibres from the more proximal branches of the nerve gradually merged with those from the terminal divisions. The most proximal level at which a bundle contained terminal fibres only was 267 mm.

The combined funiculi occupied the radial quadrants of the nerve against the ulnar artery as far proximally as 179 mm. Above this level further migrations and divisions carried them ulnarwards across the anterior surface so that 25 mm. higher they occupied the antero-ulnar and radial quadrants. Between the 240 and 250 mm. levels the bundles were situated anteriorly with the flexor carpi ulnaris, flexor digitorum profundus and arterial bundles on their radial and postero-radial side and the dorsal cutaneous bundles behind and on the ulnar side. Above this the fibres were more widely dispersed though, until the level at which most of the fibres in the nerve were collected into a single bundle (279 mm.), they remained concentrated anteriorly. In the epicondylar groove they were arranged over the anterior and medial half of the nerve. Above this they occupied the anterior quadrants and subsequently the anterior and lateral quadrants in which they were concentrated as far as the 330 mm. level.

The pattern of the bundle group, each of which was composed of both muscular and cutaneous fibres, showed 100 changes prior to their fusion with other bundles at 251 mm. and the longest section with a constant pattern was 7 mm.

The Dorsal Cutaneous Nerve of the Hand.

The dorsal cutaneous branch joined the nerve at 80 mm. and was traced as an independent bundle group for 171 mm. The fibres had then

collected into a single funiculus which fused with a bundle containing terminal muscular and cutaneous fibres. One millimetre higher these two separated but in the process some dorsal cutaneous fibres remained with the latter.

Between 251 and 269 mm. the dorsal cutaneous bundles anastomosed with neighbouring bundles composed of fibres from the terminal branches while further proximally other fibre systems participated in the intercommunications. Up to the 279 mm. level, however, the dorsal cutaneous fibres remained relatively well localized even though they were contained in several funiculi. At this level the fibres of all branches, with the exception of some from the flexor carpi ulnaris, were collected into a single bundle in which, so far as could be ascertained, the bulk of the dorsal cutaneous fibres occupied a relatively localized position. Further divisions and anastomoses subsequently led to a wider dispersal of the fibres though some localization could still be identified as far proximally as 307 mm. beyond which level it was lost.

Between 258 and 267 mm. and 279 and 307 mm. a small bundle containing dorsal cutaneous fibres only separated from the main funiculus.

The bundles occupied the ulnar margin of the flattened nerve as far as the 187 mm. level when they gradually passed to and occupied the postero-ulnar quadrant as far as a point just below the epicondyle where they were spread over the posterior surface of the nerve. In the epicondylar groove two arrangements were observed in both of which the dorsal cutaneous fibres were placed laterally. Usually they occupied a postero-lateral (superficial) position as in this specimen, though in some they were deeply placed beneath bundles carrying fibres from the flexor carpi ulnaris and flexor digitorum profundus muscles. Above the epicondyle the fibres were concentrated postero-medially and medially—in other specimens they were observed postero-laterally.

The branch entered as 8 bundles which were reduced successively to 4, 3, 2 and 1. The fibres of the branch were arranged as a single bundle at the ulnar margin of the nerve from 157 mm. to 168 mm. but then divided into 2-4-3-2-3-4-3-4-3 and finally 2 funiculi which continued uninterruptedly from 224 mm. to 239 mm. These then fused and proceeded for another 11 mm. along the posterior surface before participating in plexus formations with funiculi carrying other fibres.

Over the 171 mm. for which this branch pursued an independent intraneural course there were 35 changes in its funicular pattern. The longest section over which the pattern was constant was 15 mm. The

significant features of the intraneural anatomy of this branch were: (1) The early reduction in number of the bundles which were still further reduced to one or two over distances up to 15 mm.; (2) the long course before any fibres merged with those of another system; (3) the sharp localization of the bundles as far as the epicondyle and the relative localization for some distance above that level; (4) the intraneural shift of the bundles and the consequent variations in the quadrant occupied by their fibres at different levels.

Though the dorsal cutaneous and combined terminal fibre bundle groups ran for comparable lengths in the nerve there was a marked disparity in the number of changes of funicular pattern in the two cases. A possible explanation of this is that the dorsal cutaneous fibres of the hand were collected into an independent bundle system at a high level thus reducing the necessity for further sorting, while in the case of the combined funiculi a greater number of exchanges was required in order to separate the fibres of the deep and superficial divisions.

Branch to the Ulnar Artery.

The branch to the ulnar artery joined the antero-lateral margin of the nerve at 107 mm. as a single bundle and continued proximally as such for 145 mm. when it fused with a bundle carrying fibres of the terminal branches of the nerve. The fibres, however, remained well localized until the 279 mm. level when they became permanently lost in a large funiculus.

The bundle proceeded along the radial margin until the distal branch to the flexor carpi ulnaris was applied to its radial side at 225 mm. It later occupied the antero-radial margin of the deep (radial) surface and, at 252 mm., anastomosed in the manner referred to above. In the groove the fibres were concentrated anteriorly before their final dispersal.

Distal Branch to Flexor Carpi Ulnaris.

The single bundle of the distal branch to the flexor carpi ulnaris entered the radial margin of the nerve at 225 mm. It proceeded first along this margin and then along the deep surface and, 24 mm. above the site of entry, was joined by the bundle of one of the two branches to the flexor digitorum profundus. The combined fibres continued in the postero-radial quadrant for 11 mm. and then, at the 260 mm. level, were joined by the funiculus of the second branch to the flexor digitorum profundus.

Branches to Flexor Digitorum Profundus.

There were two branches to the flexor digitorum profundus and each was composed of a single funiculus which, at 238 mm., joined and then

proceeded along the posterior surface, and later postero-radial aspect, of the nerve. At 249 mm. the larger of the two fused with the bundle from the distal branch to the flexor carpi ulnaris and at 260 mm. the smaller bundle joined the compound funiculus thereby outlined.

Bundle Containing Flexor Digitorum Profundus and Distal Flexor Carpi Ulnaris Fibres.

The single funiculus formed at 260 mm. in the postero-radial quadrant by the union of the fibres from the two branches to the flexor digitorum profundus and the distal branch to the flexor carpi ulnaris was traced proximally to the 267 mm. level where it fused with an adjacent bundle containing terminal cutaneous and muscular fibres. Despite further intercommunications these proximal muscular fibres remained localized at the lateral margin of the nerve at the epicondyle and to the postero-medial (superficial) surface and posterior pole above that level. At 307 mm. they were scattered over the postero-medial surface of the nerve with the remaining flexor carpi ulnaris fibres and some dorsal cutaneous fibres of the hand medial to them. Above this level the fibres could not be traced accurately owing to the possibility of intrafunicular migrations but the arrangement suggested that they were gradually dispersed over the funiculi. In the epicondylar groove they were always arranged at the lateral, that is olecranon, aspect of the nerve. In some cases they were deeply located in this situation, while in others they were more superficially placed with the dorsal cutaneous fibres of the hand deep to them.

The general intraneural topography of the fibres to the flexor digitorum profundus, as revealed by a study of dissected specimens, was as follows:

These fibres joined that surface of the nerve which was applied to the muscle and, as they ascended, moved towards the lateral (olecranon) margin in the groove where they were either superficially or deeply placed. Above the epicondyle they were collected posteriorly and postro-medially, first superficially and later deeply. In some specimens the fibres were traced round the posterior margin to the deep surface where they ascended in the postero-lateral quadrant. The bundles of this system occasionally crossed the groove either independently or in company with flexor carpi ulnaris fibres.

The Intermediate and Proximal Branches to the Flexor Carpi Ulnaris.

The intermediate branch entered the anterior margin of the nerve at 254 mm. as a single funiculus which passed to the superficial (ulnar) surface and then proceeded along it, without division or anastomosis, for 20 mm. when it was joined by a bundle from the proximal branch.

In the epicondylar groove the compound funiculus was located postero-medially. Above this region it was situated on the medial surface and at the 302 mm. level temporarily joined another mixed bundle for 2 mm. At 307 mm. it united with a funiculus, which probably contained only terminal muscular and cutaneous fibres, and remained in this bundle for 21 mm. Further anastomoses then occurred until at 331 mm. the fibres were lost in a large funiculus. They were last identified on the medial surface of the nerve midway between its anterior and posterior margins.

At 269 mm. the proximal branch, composed of three bundles, entered the lateral (olecranon) margin of the posterior surface of the nerve. 5 mm. further proximally one of these joined the bundle of the intermediate branch while the remaining 2 were reduced to a single bundle which was traced proximally to the 331 mm. level where it entered a large funiculus and could be traced no further. In the epicondylar groove these fibres, excluding those which had passed to the bundle representing the intermediate branch, were arranged at the extreme lateral (olecranon) margin of the nerve. Above the epicondyle they coursed superficially on the postero-medial aspect and at 307 mm. passed to the posterior pole. They then curved round the posterior margin to reach the deep surface of the nerve where they were lost in a large funiculus at 331 mm.

The number of branches to the flexor carpi ulnaris in the dissected specimens varied greatly. One branch usually joined the medial surface, postero-medial aspect or epicondylar margin of the nerve and coursed obliquely upwards to reach the posterior surface. These fibres continued either along this to the medial surface above the epicondyle or passed further laterally to join the fibres from the remaining branches which entered and ascended along the deep surface, postero-radial aspect, or lateral margin of the nerve. Above the epicondyle these latter fibres were concentrated about the posterior pole and then curved to reach and occupy the postero-lateral (usual) or postero-medial (occasionally, as in this specimen) quadrant. As a rule the flexor carpi ulnaris fibres crossed the groove before communicating with any other fibre system. Intercommunications occurring below the epicondyle involved bundles derived from branches from the flexor digitorum profundus.

Branch to the Elbow-joint.

The branch to the elbow-joint was composed of a small funiculus which joined the posterior margin of the nerve 7 mm. above the epicondyle and followed this margin proximally. It was situated postero-medially in the highest section examined.

SUMMARY.

(1) *Intraneural topography of the branches of the ulnar nerve.*—There was a discrete funicular localization of the branches in approximately the distal 9 cm. of the nerve. Above this level intercommunications involved the terminal muscular and cutaneous fibres. If the bundles containing combinations of these fibres be regarded as a single system then the intraneural localization held for a further 16 cm. Further proximally the dispersal and intermingling of fibres became more widespread though the reduction of bundles to one or two frequently resulted in fibres, which had been scattered over several funiculi at more distal levels, being regathered into a confined area.

The frequent reduction of the ulnar bundles to a single funiculus at and above the epicondyle obscured any localization which might have existed at higher levels though the behaviour of the fibres over the limits for which they could be studied suggested that their dissemination became progressively greater as the nerve ascended. The intraneural topography was as follows:

0 to 40 mm.		
Ulnar margin:	Anterior: Hypothenar eminence Posterior: Deep division	
Central:	Ulnar side of little finger	
Radial margin:	Fourth interspace	
40 to 48 mm.		
Ulnar margin:	Deep division	
Remainder:	Superficial division	
	Hypothenar eminence	From anterior to posterior
	Ulnar side of little finger	
	Fourth interspace	
48 to 80 mm.		
Ulnar margin:	Deep division	
Remainder:	Anterior: Hypothenar plus ulnar side of little finger	Intermingled from 69 mm.
	Posterior: Fourth interspace	
80 to 114 mm.		
Ulnar margin:	Dorsal cutaneous of hand	
Central:	Deep division	
Radial margin:	Superficial division	
	Arterial: situated anteriorly from 107 mm.	
114 to 187 mm.		
Ulnar half:	Dorsal cutaneous of hand	
Radial half:	Combined terminal cutaneous and muscular fibres	
Radial margin:	Arterial	

187 to 240 mm.

Antero-ulnar and radial quadrants:	Combined terminal cutaneous and muscular fibres
Postero-ulnar:	Dorsal cutaneous of hand
Posterior:	Flexor digitorum profundus from 238 mm.
Radial margin:	Arterial
	Flexor carpi ulnaris (distal) from 225 mm.

240 to 264 mm.

Posterior and postero-radial:	Flexor carpi ulnaris (distal)
	Flexor digitorum profundus
Postero-ulnar:	Dorsal cutaneous of hand
Antero-radial and anterior:	Combined terminal cutaneous and muscular fibres
Antero-radial:	Arterial
Medial surface (254 to 264 mm.):	Flexor carpi ulnaris (intermediate) moving from anterior to posterior

Epicondylar Region

264 to 294 mm.

Posterior surface:	Flexor carpi ulnaris (intermediate and a few proximal fibres) medially
	Flexor carpi ulnaris (proximal) laterally
	Dorsal cutaneous of hand
Medial and anterior:	Combined terminal cutaneous and muscular fibres
Lateral:	Posterior: Dorsal cutaneous of hand
	Anterior: Flexor carpi ulnaris (distal)
	Flexor digitorum profundus
	Few terminal cutaneous and muscular fibres

Alternative distribution at the epicondyle: At the lateral margin the dorsal cutaneous fibres may be anterior to the remaining fibres.

Supracondylar region

294 to 307 mm.

Anterior margin and deep aspect:	Combined terminal cutaneous and muscular fibres
Medial or superficial aspect:	Flexor carpi ulnaris (intermediate and a few proximal fibres)
	Dorsal cutaneous of hand
Postero-medial quadrant:	Dorsal cutaneous of hand
	Flexor carpi ulnaris (distal)
	Flexor digitorum profundus
Postero-medial moving to deep surface:	Flexor carpi ulnaris (proximal)

At 331 mm. the flexor carpi ulnaris fibres were localized on the superficial and deep surfaces.

Alternative distribution above the epicondyle: Flexor digitorum profundus, flexor carpi ulnaris and dorsal cutaneous fibres usually ascend in the postero-lateral quadrant.

For purposes of comparison the localization reported by previous investigators is shown in Table III.

TABLE III.—INTRANEURAL TOPOGRAPHY OF THE ULNAR NERVE (UPPER ARM).

Branch	*Stoffel*	*Marie, Meige and Gosset*	*Dejerines and Mouzon*	*Kraus and Ingham*
Flexor carpi ulnaris	Antero-medial	Medial	Lateral	Medial
Flexor dig. profundus	Postero-medial	Postero-lateral	Lateral	Medial: In the same position as those to the flexor carpi ulnaris or posterior to them
Intrinsics	Posterior	Anterior and medial	Medial — arranged from anterior to posterior: Hypothenar Interossei Adductor pollicis Flexor pollicis brevis	Antero-lateral
Cutaneous	Antero-lateral	—	Antero-medial	Antero-medial: palm Antero-lateral: ulnar aspect of hand Postero-lateral: dorsal cutaneous of hand

(2) *The length of branches as separate and independent bundle systems within the nerve.*—The branches could have been safely separated without damaging or interfering with the fibre-architecture of the nerve for the following lengths:

Deep muscular division	90 mm.
Entire superficial (cutaneous) division from the site of its origin	90 mm.
Individual branches within the superficial (cutaneous) division:	
(*a*) Hypothenar eminence	52 mm.
(*b*) Ulnar side of little finger	48 mm.
(*c*) Fourth interspace	48 mm.
Combined deep and superficial divisions—as measured from the site of terminal division of the nerve	250 mm.
Dorsal cutaneous of hand	171 mm.
Branch to ulnar artery	145 mm.
Flexor digitorum profundus	(i) 11 mm.
	(ii) 22 mm.
Combined flexor digitorum profundus and distal branch to flexor carpi ulnaris	7 mm.

Flexor carpi ulnaris:		
(*a*) Distal branch		24 mm.
(*b*) Intermediate branch		20 mm.
(*c*) Proximal branch	Funiculus (i)	5 mm.
	Funiculus (ii+iii)	62 mm.
(*d*) Combined intermediate branch and funiculus (i) of proximal branch		28 mm.

(3) *The constancy of the funicular pattern.*—15 mm. was the longest section for which the pattern remained constant and this segment extended upwards from the epicondylar level. In the 11·5 cm. proximal to this segment there were 55 changes of pattern and the longest section without a change was 10 mm. Below the epicondyle there were 250 changes in the pattern and the longest section with a constant pattern was 6 mm.

Discussion.

The conflicting views expressed on intraneural topography in previous reports may now be reconciled on the basis of the present findings.

When McKinley (1921) and Kilvington (1940), in their experimental studies, produced partial and localized lesions of a nerve—both oddly enough at high levels—funiculi were severed at a point where considerable diffusion and intermingling of fibres had already occurred so that each bundle would therefore contain fibres from several branches. At distal levels, however, the fibres would have a different funicular distribution and would ultimately be arranged in separate bundles corresponding to the individual branches. The widespread Wallerian degeneration observed at lower levels and in most, if not all, of the peripheral branches was therefore only to be expected.

On the basis of the present findings for the nerves of the upper limb it seems reasonable to assume that the different response to nerve stimulation observed by Langley and Hashimoto (1917) and by McKinley (1921) was due to the different level of stimulation in each case. In the experiments of the former, individual bundles of the common peroneal nerve were stimulated at the neck of the fibula where each contained fibres derived solely or predominantly from a single muscle. The response was consequently a sharply localized one. A diffuse response was, on the other hand, inevitable in McKinley's experiments since sciatic nerve bundles were stimulated at the ischial tuberosity, at which level their constituent fibres would, owing to the reassortment of fibres in progress in the proximal portion of the nerve trunk, be derived from several sources.

The localized peripheral effects resulting from stimulation of different quadrants of a nerve exposed at operation and of partial nerve lesions

with a correspondingly restricted localization may be similarly accounted for. It would appear that the levels of stimulation in the studies of Marie, Meige and Gosset (1915) and Kraus and Ingham (1920*a*, *b*), and the levels of the partial lesions in the clinical cases investigated by Dejerine, Dejerine and Mouzon (1915) were such that the involved groups of fibres were destined for specific branches and localized in sufficient numbers to give, in each instance, a relatively local peripheral response or effect. Kraus and Ingham's (1920*a*, *b*) observation that stimulation of the proximal part of a nerve failed to elicit contraction of muscles which were supplied by its distal portion is accounted for by the fact that at proximal levels the dissemination of distal branch fibres is well advanced, if not complete, while fibres from the branches to more proximally innervated muscles are concentrated in superficial funiculi and are consequently more accessible.

The Significance of the Intraneural Plexus.

It has been suggested (Langley and Hashimoto, 1917; Kraus and Ingham, 1920*b*; Goldberg, 1924; and O'Connell, 1936) that the purpose of the intraneural plexuses is to assemble the requisite afferent and efferent fibres for each branch from the appropriate segmental sources. In this way they would represent a peripheral continuation of the process initiated in the large limb plexuses. The present findings offer more direct evidence in support of such an assumption. Reference to the charts will indicate the manner in which the fibres for a particular branch were gradually collected together as they travelled distally towards the point of branching.

Such an explanation, however, only partly accounts for the existence of the plexuses. The present findings suggest that the number of communications was far greater than that necessary to achieve the requisite sorting of fibres. Furthermore the funiculi of certain branches took part in plexus formations distal to the site of branching when it might reasonably have been expected that there had already existed ample opportunity to effect the necessary reassortment within the nerve. More important still, however, were those occasions when two funiculi anastomosed to form a common bundle which proceeded, without any intermixing of their constituent fibres, and later divided to reproduce the original two bundles. Such communications, though not common, were nevertheless sufficiently frequent to suggest that factors, in addition to that referred to above, operate in producing plexus formations. Doubtless many plexuses are the product of mesenchymal condensations which occur during development regardless of the destination and function of the fibres.

The Nature, Extent and Peripheral Effects of Injury to a Nerve.

The nature, extent and peripheral effects of injury sustained by a nerve as the result of trauma are influenced, to some extent, by the funicular pattern at the site of injury. Furthermore, the compactness of the funiculi, which depends on the looseness of the supporting epineural framework and on the amount of fat which it contains, is a factor which should be taken into consideration when studying the results of nerve injury. There is usually more interfunicular connective tissue where the bundles are small and numerous than where they are large and few in number while the amount of adipose tissue varies in the same and different subjects, on the two sides of the body, and at different levels along the same nerves but is, as a rule, related to the general obesity or otherwise of the individual (Sunderland, 1945*b*).

The effects of a blow or compression are minimized when the nerve is composed of many small, widely separated, and loosely arranged funiculi which are free to move and spread. Since, however, the funiculi cover a wider area the chances of damage consequent on a penetrating injury are increased though, for the reasons given, the involvement is more likely to be localized to one or a group of neighbouring funiculi. If, on the other hand, the nerve is composed of a single or a few large funiculi an injury is more likely to involve a larger number of fibres. This disadvantage is offset to some extent, however, by the smaller area occupied by the nerve.

Dustin (1918) claims to have demonstrated that when the perineurium is breached all the fibres ensheathed within it rapidly degenerate from which it follows that a partial injury involving a large funiculus will be productive of more damage than one breaching the perineurium of a small bundle. The consequences of partial lesions will therefore be more severe when the nerve is damaged at a point where the funiculi are large and reduced in number than when the damage involves a richly funiculated zone. In the former Dustin believed total resection and suture to be justified while in the case of the latter he recommended local excision of the involved segment only and suture. If the original observation is correct the policy advocated by Dustin has much to recommend it. Unfortunately it has a very limited application since the unpredictable form of the pattern prevents any assessment of the size and number of bundles at the site of injury. Dustin believed that the number of bundles was greater in the region of branching but this, as has been shown, is not invariably the case. Moreover, it is the size, not the number, of the bundles which is the significant factor and there is no evidence that

the bundles are consistently smaller or larger at the site of branching. It is worthy of note that in the upper arm the funiculi of the median, ulnar and radial (spiral groove) nerves are frequently reduced to a small number of large bundles while in the case of the ulnar and radial nerves the number often undergoes a further reduction to one.

The effect of partial nerve section depends on the level of injury and the particular segment injured. Owing to the reassortment of fibres in progress in the proximal portion of the nerve and to the fibre-composition of funiculi at high levels the injury may involve those bundles which contain only a few of the fibres of some, or all, of the branches so that the resultant loss of function could not be detected clinically. This most probably accounts for Sherren's (1907) observation that a third of a nerve can be divided without producing any demonstrable motor or sensory loss. On the other hand at quite high levels the fibres of a branch, particularly those to proximally innervated muscles, may be confined to one or two bundles, either alone or in combination with others. Of interest in this connection is that arrangement whereby fibres, which have been widely dispersed in their ascent, are later regathered and sharply localized owing to the coalescence of the bundles containing them. Under these circumstances the injury could conceivably involve bundles which contained all or the majority of the fibres of a particular branch in which case the result would be clinically demonstrable and sharply localized. For reasons already discussed the chances of this occurring diminish as the nerve is ascended.

The Influence of the Intraneural Plexus on the Rate and Order of Regeneration.

Seddon, Medawar and Smith (1943) have recently directed attention to the possible influence of the intraneural plexus on the regenerative process following lesions which are not of uniform severity across the nerve. It would appear from their illustrations and account that they proceeded on the assumption that the plexus was not a continuous process but, at certain levels, was localized and transversely disposed over the entire nerve. Fibres from a unit area above the plexus were shown to be widely disseminated over the nerve below it, while the fibres for a branch taking origin from a point just below the plexus were collected from wide area immediately above the latter.

On this basis they postulated that when the densest part of the scar lay between the origin of a branch and the plexus, and therefore involved the collected branch fibres, regeneration in the latter would be delayed

longer than in those which traverse less dense scar. As a result of this the order of regeneration would become irregular. This was in accord with their experience that the rate and order of regeneration were often irregular when the lesion was situated just above the site of branching. If, on the other hand, the lesion were central to the plexus, those fibres traversing the less densely scarred area would reach the plexus in advance of those confronted by dense scar. Of the former some, on being redistributed by the plexus, would, because of the wide scattering which it induces, reach the branch. Regeneration in such a case would proceed rapidly and regularly though a reduced number of regenerating axons would reach the branch.

It has now been established that funicular intercommunications occur at frequent intervals along the entire length of the nerve and that at any one level a proportion only of adjacent bundles are involved. The redistribution of fibres effected is therefore both gradual and local and becomes more extensive only as the changes are summated at higher levels. Furthermore there is considerable variation in the distance above the origin of a branch before its fibres are sufficiently dispersed to eliminate any significant localization and the only justifiable generalization would be that the fibres of branches usually retain a significant localization in the nerve for considerable distances above the site of branching. Consequently there can be no distinction between lesions situated above and below the level of the plexus as suggested by Seddon, Medawar and Smith while a lesion which is not of uniform severity across the nerve, even if situated at a considerable distance above the site of branching, could result in the obstruction of all the fibres destined for a branch.

Though the assumption of Seddon, Medawar and Smith concerning the extent and character of the redistribution of fibres effected at any one level has not been substantiated their observation concerning the disturbed behaviour of the regenerative process when the lesions are adjacent to the origin of branches has been confirmed—the additional significant point is that lesions well above the origin of branches may also have the same effect.

The Repair of Injured Nerves.

Mobilization.—When mobilizing a nerve the distance for which a branch may be safely stripped without damaging the remaining funiculi and fibres in the nerve trunk is determined by the intraneural length over which the branch bundles maintain their individuality. Values for those distances have been given. Also of importance in this connection is the

reorientation, which frequently involves extensive migrations, of bundles or bundle groups within the nerve.

Resection and suture.—The ideal to be aimed at when suturing a nerve is full restoration of the funicular pattern by correct end-to-end apposition of corresponding funiculi. Though this is an ideal which, for technical and other reasons, can but rarely be achieved every attempt should be made to maintain the correct and *appropriate* axial disposition of the proximal and distal segments regardless of the length of the resected portion since, despite the lack of correspondence of the funicular pattern at each cut end, there is a quadrantic localization of some significance which should not be neglected.

The length of nerve which can be resected and yet leave the same funicular pattern at the surfaces of the proximal and distal segments varies over limits which have been given for each nerve but averages between 0·25 mm. and 5 mm. There is considerable variation, depending on the level, in the length which may be resected without substantially disturbing the intraneural localization of branch fibres but, owing to the fact that intercommunications within bundle groups modify the pattern but not the localization, the length is much greater than that over which the pattern remains absolutely constant. Thus the last 7 cm. of the radial nerve could be resected without greatly disturbing the quadrantic localization though obviously the resection of branches and branch bundle groups must leave fibres above the level of resection without corresponding funiculi below the site of suture.

As a rule resection of more than a few millimetres will leave the opposing nerve ends with dissimilar funicular patterns. Some bundles or bundle groups, however, may still (depending on the length resected) correspond exactly owing to the fact that all funiculi are not simultaneously involved in plexus formations. This and the exact localization of branch bundle groups for certain lengths together with the predominant quadrantic localization which obtains until quite high levels make it advisable to maintain a correct axial alignment of the nerve ends in order to ensure that the maximum number of fibres will reach, if not their old Schwann sheaths, then at least those passing to the same structure.

Another point of considerable importance is that the preservation of the *correct* axial alignment of the nerve does not necessarily mean preservation of the *old* axial alignment since adjustments may be required to correct for changes in the quadrantic localization at two different levels. Attention has already been directed to the manner in which bundle groups, representing individual branches, alter their position in the nerve

as they ascend without, however, scattering or anastomosing with other bundle groups. Examples in point are the changing relationships of the motor and sensory fibres in the median nerve at the wrist and the course pursued by the dorsal cutaneous fibre bundles in the ulnar nerve. It is obvious that if such intraneural shifts are not corrected for by the appropriate orientation of the ends, overlapping of funiculi and the apposition of dissimilar funicular groups is inevitable. Admittedly it is often impossible to correct for this factor particularly when individual funiculi or a group of bundles migrate independently within the nerve since under such circumstances attempts to restore continuity in the bundle or bundles undergoing intraneural shift only leads to an upset in the alignment of the others.

The localization obtaining from level to level along the radial nerve was reasonably constant while in the case of the median nerve variations in the quadrantic disposition of individual fibre groups at different levels was a feature of the intraneural topography of that nerve. A changing quadrantic localization was also recorded for the ulnar nerve but not to the same degree as that observed in the median. This morphological feature undoubtedly contributes to the satisfactory results which customarily follow repair of the radial nerve and the unsatisfactory or indifferent results usually reported for the median and ulnar nerves.

It is suggested that it may be practicable on occasion, for example in the terminal portion of the radial nerve and in the median and ulnar nerves at the wrist, to isolate large and well-defined bundle groups and to suture each independently—this would go some way towards eliminating wasteful cross-shunting of regenerating axons.

Regeneration in Sutured Nerves.

The course of regeneration following suture is greatly influenced by the size, number and composition of the component funiculi and the area occupied by the fibres of individual branches within the nerve. The arrangement of the funiculi, which depends on the amount of interfunicular connective and adipose tissue, is also of significance in this respect.

If the funiculi are large and few in number at the site of suture then correct end-to-end apposition of corresponding funiculi, or funiculi with at least corresponding quadrantic relationships, should be attainable and the chances of restoring useful connections consequently improved. In these cases there is usually less interfunicular connective tissue into which regenerating axons may be directed. Recovery in such cases should

therefore be more rapid and more complete. The conditions are reversed, however, when the resection and suture are performed in a zone composed of numerous small funiculi or when the upper surface presents a few large closely applied funiculi and the lower many small widely scattered bundles. The increased amount of interfunicular connective tissue, which is usually associated with an increase in the number of funiculi and a diminution in their size, together with any increased amount of adipose tissue further separates the funiculi. Consequently not only is the correct end-to-end apposition of corresponding funiculi, or funiculi from corresponding quadrants, rendered more difficult or even impossible but the possibility of some funiculi being unavoidably directed towards the interfunicular spaces is considerable. When this occurs many regenerating axons will enter the interfunicular spaces and end blindly there. Recovery under such circumstances is slower and less perfect and the prognosis is consequently worse.

It would be advisable to inspect the nerve ends at operation and, in addition, to examine histologically the proximal and distal ends of any resected segment in order to ascertain the nature of the funicular pattern at the suture line. It would be interesting to correlate the information thereby obtained with the end-result as a preliminary step to investigating whether or not the points discussed above are of any value in arriving at a prognosis.

Dustin (1918), working on the assumption, which has not been supported in the present investigation, that the funiculi are more numerous in the neighbourhood of the origin of branches, postulated that the prognosis of nerve suture should be better the further the suture is executed from the origin of the branches.

Stopford's (1920) observations suggest that the results of high suture are better than those executed at distal levels. The present study has revealed that there are far fewer bundles at proximal than at distal levels which may well be one of the factors leading to the differences in recovery reported by him. Distally the localization obtaining is sharper but, though one might therefore reasonably expect better end-results from sutures at this level, this morphological advantage is probably offset by the presence of smaller and more numerous funiculi and the increased amount of interfunicular connective tissue separating them.

Composition of funiculi.—It is essential to have, wherever possible, opposing funiculi composed of fibres of the same type, if not actually corresponding, and for this reason the fibre-composition of individual funiculi at the site of suture is of some relevance. Thus the apposition

of funiculi containing few muscular and many cutaneous fibres to those containing Schwann sheaths passing to a particular muscle or group of muscles must inevitably result in many regenerating axons failing to reach the appropriate end-organ. The cross-sectional area occupied by individual branch fibres at the suture level also has an important bearing on the effectiveness of regeneration since if the fibres of a muscular branch occupy a large area in the nerve the chances of some regenerating axons reaching their corresponding funiculi and Schwann sheaths is increased. If, however, they occupy only a small portion of the nerve or a single small funiculus their chances of establishing correct continuity will be correspondingly reduced. The proportionate cross-sectional area devoted to the individual fibres of the several branches of each of the three nerves have been given. Reference to those values and to the funicular distribution of muscular and cutaneous fibres along the nerve will suggest the possible influence of this factor on the nature, course, extent and usefulness of regeneration.

Selective Loss of Function Following Nerve Compression.

There was no morphological feature of the funicular pattern which would account for the selective loss of function following compression of nerves (Lewis, Pickering and Rothschild, 1931; Seddon, 1943; Denny-Brown and Brenner, 1944*a*, *b*; Sunderland, 1945*c*).

SUMMARY.

(1) The intraneural topography of the radial, median and ulnar nerves has been investigated and described.

(2) There was no constant or characteristic funicular pattern for any nerve. Variations occurred at different levels along the same nerve, at the same level on the two sides of the body, and from nerve to nerve and subject to subject at any given level.

(3) Funiculi showed no constant tendency to multiply in the neighbourhood of the site of branching or to fuse at points between.

(4) In the radial nerve the number of funiculi in the axilla and brachio-axillary angle exceeded that in the intermuscular furrow which in turn exceeded that in the spiral groove where the number was frequently reduced to one.

In the ulnar and median nerves the number of bundles at the wrist corresponded. At the elbow the number in the median exceeded that in the ulnar while in the proximal half of the upper arm the number was also usually greater in the former than in the latter. In the forearm

and distal half of the upper arm the number favoured one or the other or neither. In both nerves the funiculi were most numerous at the wrist and least numerous in the axilla and proximal half of the upper arm—the marked reduction of the ulnar bundles in the epicondylar groove was a conspicuous feature.

(5) The size and number of the funiculi were inversely related at any one level.

The radial nerve was usually composed of a large number of small funiculi in the axilla and angle, of a small number of large bundles in the spiral groove and of a medium number of small and large funiculi in the intermuscular furrow. The largest funiculi were observed in the spiral groove. The median and ulnar nerves were composed of a large number of small funiculi at the wrist, of both medium-sized and small funiculi in the forearm and of a combination of large, medium and small in the upper arm.

(6) The cross-sectional area of the funiculi devoted to individual branches before intercommunications occurred has been estimated for each nerve.

(7) The funicular pattern was continually modified along the entire length of each nerve by the repeated division, anastomosis and migration of the bundles. Each of these features has been described. The longest section of any nerve with a constant pattern was 15 mm. though individual bundles and bundle groups pursued longer courses. The average length over which the pattern remained constant varied between 0·25 and 5 mm.

(8) Funicular intercommunications were of three fundamental types.

(*a*) The first involved the division and fusion of funiculi within a compact localized group of bundles whose constituent fibres were derived entirely from one branch.

(*b*) In the second the constituents of one bundle group anastomosed with the adjacent bundles of another. This involved a blending of the fibres of the two originally distinct groups.

(*c*) The third involved bundles composed of different branch fibres which had been intermingled at distal levels.

(9) The nature and extent of the redistribution of the fibres which was brought about by these intercommunications is fully described.

The dispersal of fibres occasioned by the intercommunications was effected gradually and at any one level produced only a minor degree of intraneural shift. It was the summation of the changes at successive levels, and not that at any one level, which was ultimately responsible for the widespread intermingling and dispersal of fibres. This was achieved

only at high levels where the constituent fibres of the bundles were arranged in varying combinations and proportions though each bundle did not necessarily contain fibres from all branches.

Occasionally fibres, which had been widely scattered over several funiculi at distal levels, were regathered and sharply localized further proximally owing to the coalescence of the bundles containing them.

(10) The lengths were ascertained for which the bundles of individual branches coursed as separate and distinct groups within the nerve. This was a measure of the extent to which the branches could be stripped along a nerve above the site of branching without damaging the fibres.

(11) Despite the changing plexiform character of the funicular pattern, fibres from peripheral branches pursued a localized course in the nerve for variable, though often considerable, distances above the site of branching. This has been described for each nerve.

The localization obtaining along the radial nerve was reasonably constant from level to level while in the case of the median nerve variations in the quadrantic disposition of individual fibre groups at different levels was a feature of the intraneural topography of that nerve. A changing quadrantic localization was also recorded for the ulnar nerve but not to the same degree as that observed for the median.

(12) The significance of the intraneural topography has been discussed in relation to:

(i) The nature, extent and peripheral effects of injury to a nerve.
(ii) The rate and order of regeneration following injury.
(iii) The mobilization, resection and suture of nerves.
(iv) The regeneration and prognosis following nerve suture.
(v) The selective loss of function following nerve compression.

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LEGEND TO ACCOMPANY THE DIAGRAMS OF THE RADIAL NERVE SECTIONS.

Left radial nerve. Sections viewed from above. Magnification approximately × 25.

:: Posterior interosseous fibres.
ooo / ooo Superficial radial fibres.
S Supinator fibres.
+ Extensor carpi radialis brevis fibres.
× Extensor carpi radialis longus fibres.
★ Extensores carpi radiales fibres.
△ Brachioradialis fibres.
▲ Brachialis fibres.

LEGEND TO ACCOMPANY THE DIAGRAMS OF THE MEDIAN NERVE SECTIONS.

Left median nerve. Sections viewed from above. Magnification approximately × 25.

M Thenar muscular fibres.
L Lumbrical fibres.
A Cutaneous fibres from the third interspace.
B Cutaneous fibres from the second interspace.
C Cutaneous fibres from the first interspace.
D Cutaneous fibres from the radial side of the thumb.
ooo / ooo Combined muscular and cutaneous fibres from the thumb and first interspace. Lumbrical fibres above 234 mm.
P Palmar cutaneous fibres.
S Flexor digitorum sublimis fibres.
I Anterior interosseous fibres.
F_1 Proximal common flexor fibres.
F_2 Distal common flexor fibres.
T Pronator teres fibres.
:: Combined terminal and flexor digitorum sublimis fibres. Palmar cutaneous fibres above 295 mm.

LEGEND TO ACCOMPANY THE DIAGRAMS OF THE ULNAR NERVE SECTIONS.

Left ulnar nerve. Sections viewed from above. Magnification approximately × 25. Sections beyond 331 mm. are not to scale.

M Deep (muscular) division fibres.

★ Cutaneous fibres from the hypothenar eminence.

\+ Cutaneous fibres from the ulnar side of the little finger.

× Cutaneous fibres from the fourth interspace.

⁝⁝⁝ Combined terminal cutaneous fibres.

⁘ Combined terminal muscular and cutaneous fibres.

ooo Dorsal cutaneous fibres of the hand

△ Flexor carpi ulnaris fibres.

▲ Flexor digitorum profundus fibres.

A Fibres to the ulnar artery.

J Fibres to the elbow-joint.

THE ROLE OF GALVANISM IN THE TREATMENT OF DENERVATED VOLUNTARY MUSCLE IN MAN.

BY SHIRLEY JACKSON.

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ALTHOUGH the effect of galvanism on the structure and shrinkage of denervated muscle has been very thoroughly investigated experimentally, there is little, if any, direct evidence derived from observations in Man. Doupe, Barnes and Kerr (1943) investigated its effect in Man indirectly by studying the rate of recovery of muscles treated with and without galvanism after suture of the radial nerve. Their results suggested that galvanism was ineffective, but the criterion chosen was one which might have been affected by factors other than galvanism, and animal experiments suggest that the dosage used by them—15 to 30 moderate contractions five to six times a week—is one which, although it is in common use clinically, is too small to be effective: in consequence the clinical application of galvanism is still a controversial matter. Langley (1915) carried out experiments on rabbits which suggested that it was of no value, while Chor (1939) concluded that it was actually harmful. Fischer (1939) pointed out that Langley had used so weak a current that only the superficial muscle fibres were stimulated. By using a maximal stimulus and giving a greater number of contractions than Chor had done he found that denervated rat muscle lost less weight, contracted more powerfully on stimulation, and fatigued less easily than untreated control muscle. Hines (1942) and Hines, Thomson and Lazere (1943) studied the effects of electrical stimulation and of immobilization, both before and after reinnervation and found that stimulation, as well as retarding muscle wasting, accelerated recovery of muscle weight and strength, though it did not affect the time of onset of recovery. They also found that there was a direct relationship between strength and effectiveness of stimulus, and that the effect of treatment was greatest early after denervation and declined as the duration of denervation increased. Gutmann and Guttmann (1942 and 1944) confirmed the findings of Fischer and Hines and made quantitative experiments on the differences produced by varying the strength, duration and frequency of stimulation. In denervated peroneal muscles of rabbits, they found that wasting was greatly reduced though not prevented by stimulating with a current of such strength as to give

strong contractions for twenty to thirty minutes daily. A reduction in the strength of current or duration of treatment considerably reduced its efficacy, but an increase in the duration of application from twenty to thirty minutes caused only a slight improvement. They found that with adequate treatment the muscle fibres remained large, and fibrosis was minimal. This effect was most marked in the superficial parts of the muscle where, presumably, the stimulus had been most effective. It therefore seemed likely that galvanism might prove valuable in the treatment of peripheral nerve injuries, but in clinical practice there are certain conditions not found in the animal experiments:

(1) The muscles to be stimulated are much larger than those in the rabbit or rat, and therefore are more difficult to exercise adequately.

(2) Frequent and prolonged treatment is probably required, but a man may be obliged to return to work during the long period when he is waiting for recovery to occur.

The purpose of this present work is to determine:

(1) Whether or not electrical treatment, such as can reasonably be given clinically, produces any beneficial effect.

(2) If so, what is the effective dosage and frequency of treatment.

(3) Whether the effect justifies the time spent by the patient in receiving treatment.

(4) When the treatment should begin.

(5) How long it should continue.

Material.

Patients with ulnar or combined median and ulnar nerve lesions were studied, and wasting of the hand was estimated from time to time by measuring the volume of displaced fluid. The patients were divided into two groups, one treated with and the other without galvanism, and the difference in rate of wasting in the two groups was compared. 161 subjects were examined, but in only 92 was it possible to make readings frequently enough for them to be of use. 70 of the subjects were healthy soldiers or airmen between the ages of 20 and 30; there were 7 children and 4 women; the rest were older men. 54 of the adults showed complete denervation of the affected muscles; in the remainder reinnervation was in progress.

On admission, a detailed history was taken with special reference to previous physiotherapy and immobilization; examination included assessment of joint stiffness and wasting, contracture, voluntary power, electrical excitability, and, in some cases, electromyographic activity of the muscles. There were many variable factors. The lesions ranged from gunshot

wounds with gross trauma, sepsis and a large gap in the nerve to lesions in continuity such as are caused by closed fractures. Very few patients were admitted immediately after injury, and in some the length of history was over a year; a few paetients were studied until three years after injury.

Grouping.—The patients were grouped according to:—

(1) The type of lesion.
(2) The level of lesion.
(3) The time interval between injury and first volumetric measurement.

The method of grouping was as follows:—

Type of nerve lesion.	1. Division.
	2. Lesion in continuity (with a subdivision, traumatic ulnar neuritis).
Level of lesion.	1. High—proximal two-thirds of arm or higher.
	2. Medium—distal one-third of arm and proximal one-half of forearm.
	3. Low—distal half of forearm and hand.
Length of history.	1. Early—less than six months between injury and first volumetric reading.
	2. Fairly early—between six and twelve months.
	3. Late—over twelve months.

Combinations of these variables gave 27 groups, each of which was divided as evenly as possible into those to be treated with or without galvanism. This method of grouping was useful for balancing the variables in the two large groups—treated and untreated—but the number of cases in each sub-group was too small and there were still too many variable factors for cases in the same sub-group treated with and without galvanism to be directly compared with each other. In the material used for the assessment of the rate of wasting during denervation, there was paralysis of the median as well as of the ulnar muscles of the hand in 18 per cent. of the treated and 20 per cent. of those not treated.

Treatment.—In the treated group galvanism was given to each paralysed muscle six days in each week. The stimuli were given at the rate of 30 a minute, which gave the muscle ample time to relax between contractions. Fatigue was avoided by dividing the 90 contractions into three equal groups with two intervals of at least a minute, so that the paralysed muscles were given 30 contractions in turn, repeated thrice. The tolerance of the skin to galvanism and of the patient to pain limited

the strength of the current used: but the aim was to obtain a contraction strong enough to move the joint laterally with gravity eliminated, and this was usually achieved without difficulty. For the interosseous muscles, one button electrode was placed on the palmar, and the other on the dorsal surface of the muscle. An attempt was made to keep other forms of treatment identical in the two groups. Passive movements, active exercises, massage and occupational therapy were given, and if there was paralytic deformity the hand was splinted in such a way as to preserve mobility.

Method.

Wasting was estimated by measuring the volume of the paralysed hand, expressed in terms of the weight of fluid displaced. In some cases the normal hand was also measured. The hand was immersed in industrial alcohol, which eliminates bubble formation, up to a tattooed level on the wrist about 3 cm. above the pisiform; at this level the circumference of the wrist is fairly constant. The fluid displaced was weighed in dried bottles of known weight. Inaccuracies due to unsteadiness of the patient's arm had to be overcome. He sat on a heavy, firm stool with an adjustable sliding support for the arm. The forearm was again immobilized with the hand pointing vertically downwards; the hand and wrist were free to enter the measuring vessel. This was a glass cylinder mounted on a metal base with an outlet tube running to within a few inches of the top; the vessel was mounted on a jack. By filling the vessel and then displacing fluid by jacking it up until the surface was level with the tattooed marks, the volume of the hand could be obtained. The machine gave an intrinsic error of only ½ per cent. Greater variations arose from factors other than changes in wasting, but over sufficiently long periods they were insignificant compared with the changes in volume due to atrophy of the muscles. The mean of two measurements was taken at each examination. The readings were expressed in grammes of alcohol and this unit was retained except in calculating the final combined results. Since very few patients were first seen soon after injury, the method was only of value in comparing the wasting that had occurred between two or more readings; absolute estimates were not possible. The units used here express the loss of volume of the muscles in relation to the total volume of the hand. If this loss could be expressed in relation to muscle volume it would appear much greater. Abramson and Ferris (1940) give the percentage volume of normal muscle in the hand as 15·5 per cent. so that all values obtained in this study would have to be multiplied by 4, 5 or even more to give a true percentage loss of volume in the denervated muscle.

Records were kept of:

(1) The recovery and degree of voluntary power (using the method recommended by the Medical Research Council, 1943).

(2) The ability to use the recovering muscles independently.

(3) The electrical reactions. These were usually elicited with Bauwens' machine (Bauwens, 1941) which gives quantitative readings.

(4) In the cases observed most recently electromyographic studies were made (Weddell, Feinstein and Pattle, 1943); the presence or absence of

fibrillation action potentials and fibrillation irritability, or of motor unit action potentials or irritability gave information about the state of reinnervation of the muscle.

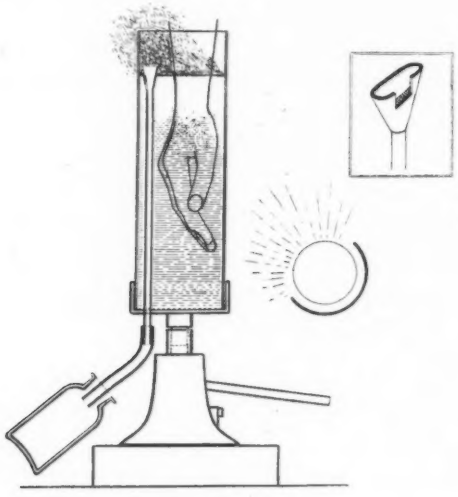

FIG. 1.

FIG. 1.—Diagram of the measuring vessel. The level of the fluid on the wrist is illuminated by the light shining from below and lighting only the area of skin beneath the surface. The inset diagram is of the upper end of the outlet tube which was designed to break the meniscus.

EXPERIMENTAL VARIABLES.

Errors in technique were partly controlled by taking the mean of two readings. Hour-to-hour changes in volume of the hand are to be expected, and may be brought about by muscular contraction (Martin, Woolley and Miller, 1932) (Anrep, 1934 and 1935), changes in temperature (Grant and Pearson, 1937), and such factors as painful stimuli, mental effort (e.g. mental arithmetic) and taking a deep breath (Abramson and Ferris, 1940).

An attempt was made to determine what order of error might be expected, and, if it was significant, how it could be eliminated.

Effect of changes in temperature.—Measurements were taken when the hand was cold, cool, and after immersing the feet in hot water until the temperature of the hands was about 34° C. and the patient was sweating. The results in Table I show that the volume of the hand increases with

TABLE I.—EFFECT OF CHANGE IN TEMPERATURE ON THE VOLUME OF THE HAND.

	Paralysed side			*Normal side*		
	Volume of hand in grammes of spirit			*Volume of hand in grammes of spirit*		
Case	*Cold*	*Hot*	*Difference*	*Cold*	*Hot*	*Difference*
1	338·5	350·75	12·25	346·0	362·75	16·75
2	309·75	322·75	13·0	351·0	376·25	25·25
3	338·0	356·0	18·0	374·0	389·0	15·0
4	311·25	319·0	7·75	307·0	311·5	4·5
5	318·0	331·25	13·25	333·25	352·5	19·25
6	321·5	331·5	10·0	303·0	308·5	5·5
7	364·0	389·0	25·0	421·0	435·5	14·5
8	307·0	318·0	11·0	338·5	352·0	13·5
9	293·5	305·0	11·5	297·75	315·5	17·75
	Average difference 13·53			Average difference 13·59		

the temperature. The greatest increase observed was 7·1 per cent. of the volume of the hand, but this was brought about by artificial conditions designed to produce full vasodilatation. The variation was not constantly greater or less on the normal side, and the average variation was the same on both sides.

Immediate effect of galvanic treatment on the volume of the hand.—Both hands were immersed immediately before and after treatment of the paralysed hand. Table II shows that in 8 out of 10 cases the volume

TABLE II.—IMMEDIATE EFFECT OF GALVANIC TREATMENT ON THE VOLUME OF THE HAND.

	Paralysed side			*Normal side*		
	Volume of hand in grammes of spirit			*Volume of hand in grammes of spirit*		
Case	*Before treatment*	*After treatment*	*Difference*	*Before treatment*	*After treatment*	*Difference*
1	350·5	344·5	−6·0	386·25	384·0	−2·25
2	368·25	366·25	−2·0	—	—	—
3	372·5	364·75	−7·75	425·25	435·0	+9·75
4	396·25	385·0	−11·25	439·25	434·0	−5·25
5	345·0	338·0	−7·0	—	—	—
6	314·0	315·0	+1·0	—	—	—
7	300·5	300·75	+0·25	—	—	—
8	322·0	319·5	−2·5	305·5	299·5	−6·0
9	305·25	304·75	−0·5	326·5	328·5	+2·0
10	370·5	369·5	−1·0	—	—	—

of the affected hand decreased after galvanic treatment. In the two cases in which there was an increase, it was very slight. In only one case was there a greater fall in volume of the normal (untreated) hand than on the affected side. The skin temperatures were not measured, and it is possible that the treated hands became cold during treatment, thus producing a fall in volume.

Effect of venous compression on the volume of the hand.—The upper arm was compressed with a sphygmomanometer cuff at 80 mm. of mercury until the veins of the forearm and hands were engorged. Table III

TABLE III.—EFFECT OF VENOUS COMPRESSION ON THE VOLUME OF THE HAND.

	Paralysed side			*Normal side*		
	Volume of the hand in grammes of spirit			*Volume of the hand in grammes of spirit*		
Case	*Before compression*	*After compression*	*Difference*	*Before compression*	*After compression*	*Difference*
1	364·0	377·0	+13·0	422·0	430·0	+8·0
2	369·5 (1)	374·0				
	(2)	377·0	+7·5			

shows that with full venous compression for five minutes there was an increase of 2 per cent. in the volume of the hand.

Effect of occupational therapy on the volume of the hand.—The volume of the hands was measured before and after vigorous fine manual work for twenty minutes. Table IV shows that the change in volume was in

TABLE IV.—EFFECT OF OCCUPATIONAL THERAPY ON THE VOLUME OF THE HAND.

	Paralysed side			*Normal side*		
	Volume of the hand in grammes of spirit			*Volume of the hand in grammes of spirit*		
Case	*Before work*	*After work*	*Difference*	*Before work*	*After work*	*Difference*
1	309·5	305·75	−3·75	316·0	315·0	−1·0
2	305·0	309·0	+4·0	335·0	338·5	+3·5
3	302·0	296·0	−6·0	308·0	304·5	−3·5
4	257·5	255·5	−2·0	304·0	294·0	−10·0

the same direction on the two sides but not necessarily of the same degree.

When the volume of the paralysed hand is expressed, first as a percentage of the normal under the same conditions, and second as a percentage of its own highest value it is seen that there is a direct, though not exact, correlation between the volume of both hands. An example is given in fig. 2, A, B, and C. In the same case a series of readings was made on both hands, and it can be seen from fig. 3, A, B. and C, of which B shows the most uniform readings, that there is a small day-to-day variation in the volume of both hands which can be partly eliminated by expressing the volume of the paralysed side as a percentage of the normal.

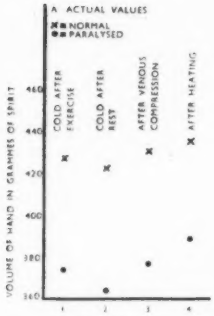

FIG. 2 A.

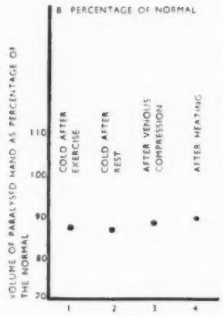
B PERCENTAGE OF NORMAL
VOLUME OF PARALYSED HAND AS PERCENTAGE OF THE NORMAL
COLD AFTER EXERCISE
COLD AFTER REST
AFTER VENOUS COMPRESSION
AFTER HEATING

FIG. 2 B.

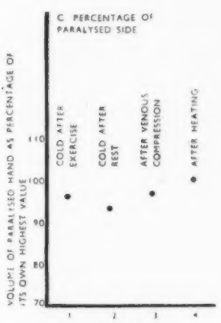
C PERCENTAGE OF PARALYSED SIDE
VOLUME OF PARALYSED HAND AS PERCENTAGE OF ITS OWN HIGHEST VALUE
COLD AFTER EXERCISE
COLD AFTER REST
AFTER VENOUS COMPRESSION
AFTER HEATING

FIG. 2 C.

FIG. 2.—The effect of different conditions on the volume of the hand—(A) actual values, (B) the volume of the paralysed side expressed as a percentage of the normal, (C) the volume of the paralysed side expressed as a percentage of its own highest value.

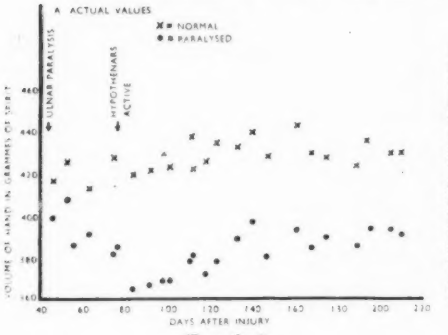

FIG. 3 A.

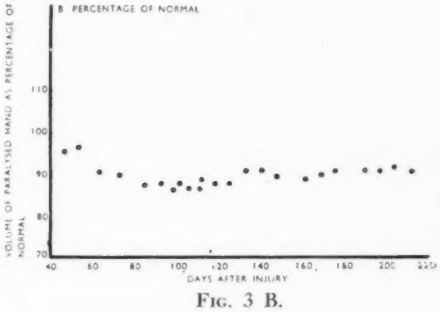

FIG. 3 B.

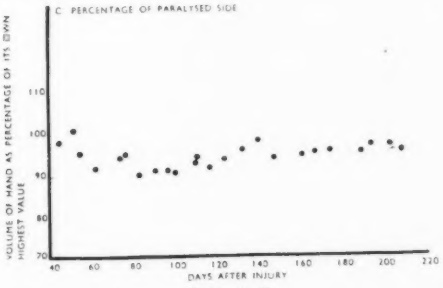

FIG. 3 C.

FIG. 3.—Day-to-day variations in volume—(A) actual values, (B) the volume of the paralysed hand expressed as a percentage of the normal, (C) the volume of the paralysed hand expressed as a percentage of its own highest value.

Results.

For each case a graph was made, recording the volume of the hand in terms of grammes of spirit at intervals measured in days after injury. Operative treatment, immobilization, progress of voluntary power, electrical reactions and electromyographic findings were also recorded chronologically.

Rate of Wasting in Unrecovered Cases Based on the Volume of the Paralysed Side Only.

Because of differences in the length of history and, correspondingly, the degree of wasting present when the patient was first seen, the data were grouped on the basis of time into periods of a hundred days each, from the date of injury until 400 days after injury. After 400 days all cases were grouped together. Within the 100 day groups, the rate of decline of volume was arbitrarily assumed to be constant. In fact, it is probably otherwise, but the variables were such that a curve could not be drawn with any degree of certainty. The method suggested for eliminating day-to-day variations—expressing the volume of the paralysed hand as a percentage of the normal—was not used in this particular calculation, because the number of readings of the paralysed hands was great, so that these variations were automatically decreased, while the comparatively small number of readings on the normal hands would have diminished the amount of available material considerably.

Table V.—Details of the Material Analysed by this Method.

Group	*Days after injury*	*Treatment*	*Number of cases*	*Cases of combined median and ulnar paralysis*
1	0—100	Galvanism	8	1
2	0—100	No galvanism	4	0
3	100—200	Galvanism	8	1
4	100—200	No galvanism	14	4
5	200—300	Galvanism	13	3
6	200—300	No galvanism	11	2
7	300—400	Galvanism	10	1
8	300—460	No galvanism	10	3
9	400+	Galvanism	3	2
10	400+	No galvanism	10	2

In order to combine the readings for cases in one group on one graph, the volume found by displacement was converted into a percentage. A single reading on the normal hand or the first reading on the paralysed side was unreliable. Therefore it was thought more accurate to make each reading a percentage of the mean volume of the paralysed hand during the 100 day period. The regression line was worked out for each

graph. This line should run through 100 per cent. at roughly 50 days, and its slope gives the rate of wasting. A fallacy arises in that in some cases the first reading was made many days after the beginning of the 100 day period, so that some high readings which are really the first of a single case, appear in the composite graph well into the 100 day period.

The data obtained in Groups 1 to 6, i.e. the rate of wasting up to 300 days after injury, with and without galvanism, were subjected to statistical analysis. As will be seen later, the data in Groups 3 to 6 establish the conclusions with certainty, so that in the subsequent groups which were comparable with these groups, and were subject to similar errors of chance, a statistical analysis was considered unnecessary. A special error which arose in Group 1 requires separate consideration.

Group 1.—In this group there were 8 cases, in one of which there was also paralysis of the median nerve. In only two cases was the first reading taken before the 60th day, because the patients did not come under observation before that time. This difficulty introduces an error in the graphs for the time group 0 to 100 days.

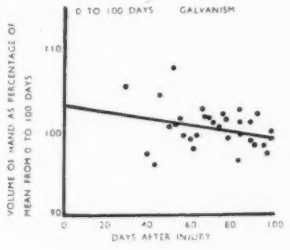

FIG. 4.

FIG. 4.—Rate of wasting between 0 and 100 days after injury in patients treated with galvanism. The slope of the regression line was found to be only $-0{\cdot}0389 \pm 0{\cdot}0231$ per cent. per day, and the chances that the recorded decrease could be due to luck of sampling alone were found to be 1 in 10. This slope represents a loss of 3·89 per cent. of the volume of the hand in 100 days.

Group 2.—This group was made up of 4 cases of isolated ulnar paralysis not treated with galvanism. In 2 cases the first readings were before 30 days, and in the other 2, between 45 and 55 days. Thus the average first reading is earlier than in Group 1.

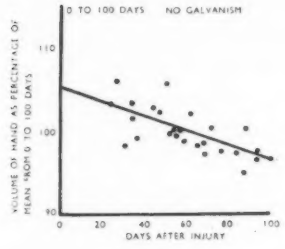

FIG. 5.

FIG. 5.—Rate of wasting between 0 and 100 days after injury, in patients treated without galvanism. The slope of the regression line is in this case $-0{\cdot}0864 \pm 0{\cdot}0179$ per cent. per day. So high a rate of decline would occur through luck of sampling less often than once in 500 trials. The line represents a loss of 8·64 per cent. of the volume of the hand in 100 days. The difference between the slopes of the regression lines in figs. 4 and 5 is 0·0475, with a standard error of 0·0298. A difference as great as this might occur by chance once in ten trials. Thus in the first 100 days after injury there is some indication that galvanism retards but does not prevent wasting of denervated muscles.

Group 3.—In this group there were 8 cases of ulnar nerve paralysis, in one of which there was also paralysis of the median nerve. In this group and in those that follow the patients were already in hospital before 100 days after injury, so that the first of the series of readings in each case was nearer the beginning of the time period than in Groups 1 and 2.

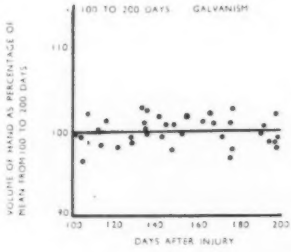

FIG. 6.

FIG. 6.—Rate of wasting between 100 and 200 days in patients treated with galvanism. The slope of the regression line was found to be $+0{\cdot}000576 \pm 0{\cdot}00898$: in other words, the regression line is virtually horizontal, and there has been no appreciable change of volume within this period.

Group 4.—These were 14 cases of ulnar nerve paralysis, in 4 of which there was also paralysis of the muscles of median innervation. Galvanism was not given.

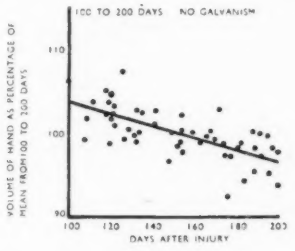

FIG. 7.

FIG. 7.—Rate of wasting between 100 and 200 days in patients not treated with galvanism. The slope of the regression line was found to be −0·0727 per cent. per day, with a standard error of ±0·0109. The chances are millions to one against so great a deviation from the horizontal being due to luck of sampling alone. This slope represents a loss of 7·27 per cent. of volume of the hand between 100 and 200 days after denervation. The difference between the slopes of the regression lines in figs. 6 and 7 is 0·0733 ±0·0149. Here there can therefore be no question of the efficacy of galvanic treatment.

Group 5.—This group treated with galvanism contained 13 cases of ulnar paralysis, in 3 of which there was also paralysis of the muscles of median innervation.

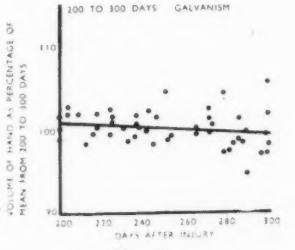

FIG. 8.

FIG. 8.—Rate of wasting between 200 and 300 days in patients treated with galvanism. Here, as in the 100-200 day period, the slope does not depart significantly from the horizontal: wasting has been virtually arrested.

Group 6.—In this group there were 11 cases of ulnar nerve paralysis, in 2 of which there was also paralysis of the muscles of median innervation.

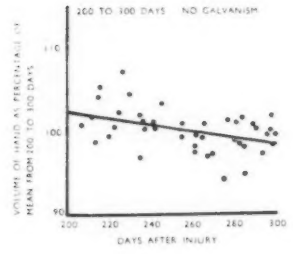

FIG. 9.

FIG. 9.—Rate of wasting between 200 and 300 days after denervation in patients not receiving galvanism. The slope of the regression line is −0·0371 per cent. per day with a standard error of ±0·0117—a small but significant decrease of volume, viz.: 3·71 per cent. between 200 and 300 days after injury. Comparison of the slopes of the lines in figs. 8 and 9 shows that between 200 and 300 days after denervation wasting had been brought to a virtual standstill under galvanic treatment, but that it continued, at a slower rate than before, when galvanism was withheld.

Group 7.—This group is made up of 10 cases of ulnar paralysis, in one of which there was also paralysis of the muscles of median innervation.

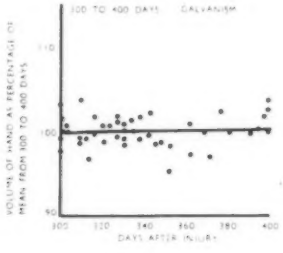

FIG. 10.

FIG. 10.—Rate of wasting between 300 and 400 days in patients treated with galvanism. It is clear that the slope of the regression line, +0·0040, does not differ significantly from the horizontal. There has been no further wasting.

Group 8.—These were 10 cases of ulnar paralysis in 3 of which there was also paralysis of the muscles of median innervation.

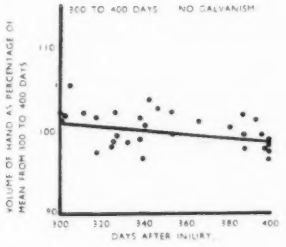

FIG. 11.

FIG. 11.—Rate of wasting between 300 and 400 days in patients treated without galvanism. The slope of the regression straight line is −0·0227 per cent. per day, representing a loss of 2·27 per cent. of the volume of the hand between 300 and 400 days. The decline is hardly significant: the process of wasting is evidently coming to an end within this period.

Group 9.—This was a group of three cases of ulnar nerve paralysis, two of which were combined with median paralysis. In each case more than 400 days had elapsed since denervation.

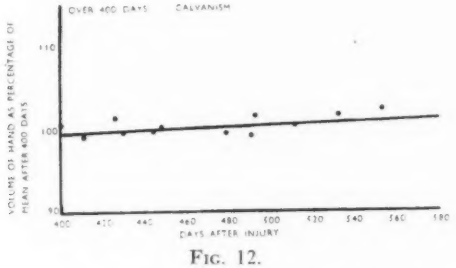

FIG. 12.

FIG. 12.—Rate of wasting later than 400 days after injury in patients treated with galvanism. Here, as before, the volume of the hand remains unchanged.

Group 10.—These were 10 cases of ulnar paralysis in two of which there was also median paralysis.

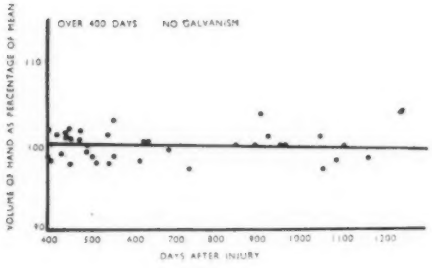

FIG. 13.

FIG. 13.—Rate of wasting later than 400 days after denervation in patients treated without galvanism. (Note different time scale.) The regression line is virtually horizontal, and wasting has definitely come to a standstill. Figs. 12 and 13 suggest that 400 days after denervation and beyond, wasting has stopped in untreated as well as in treated hands.

TABLE VI.—THE EFFECT OF GALVANISM ON WASTING.

Showing the amount of wasting in 100 days in each of these groups.

Days after injury	*Change of volume as percentage of mean of the paralysed hand in the period studied*		*Difference between* 1 *and* 2 *representing amount of wasting prevented by galvanism*
	I (*Galvanism*)	*II* (*No galvanism*)	*III*
0—100	− 3·89	− 8·64	4·75
100—200	+ 0·06	− 7·27	7·33
200—300	− 1·33	− 3·71	2·38
300—400	+ 0·40	− 2·27	2·67
over 400	+ 0·57	− 0·08	0·65

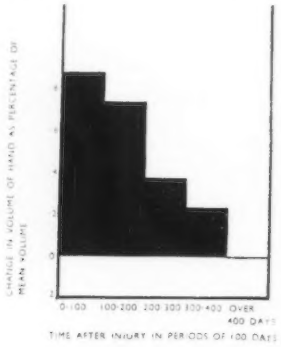
CHANGE IN VOLUME OF HAND AS PERCENTAGE OF MEAN VOLUME
0-100 100-200 200-300 300-400 OVER 400 DAYS
TIME AFTER INJURY IN PERIODS OF 100 DAYS

FIG. 14.

FIG. 14.—The rate of wasting without galvanism at different periods after denervation (column 2 of Table VI). The rate of wasting is greatest in the first 100 days after injury, and thereafter progressively falls. After 400 days there is no appreciable change.

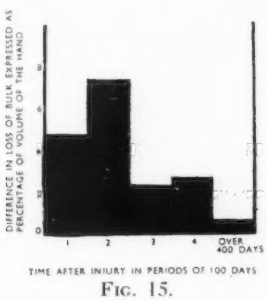

FIG. 15.

FIG. 15.—The difference in degree of wasting with and without galvanism (represented in column 3 of Table VI). When galvanism is used the rate of wasting is lower than when it is not used, though wasting is not completely prevented. On the whole the effect is greater early after denervation, though this is not demonstrated in the first two time periods (*see* fig. 15). In fig. 16 the mean time for each time period has been calculated and plotted against the rate of decline in volume of the hand in that period.

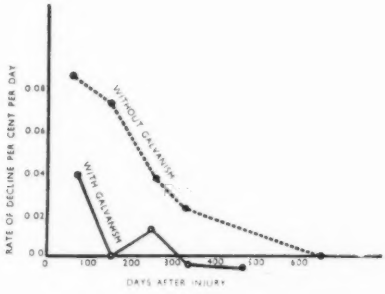

FIG. 16.

FIG. 16.—The rate of decline of the volume of the hand as a function of time with and without galvanism. When galvanism is used, wasting of the hand comes virtually to a standstill in the period 100 to 200 days and thereafter.

THE EFFECT OF GALVANISM ON WASTING IN AN IMMOBILIZED PART.

In patients treated with and without galvanism during immobilization of the upper limb, excluding the hand, the total decrease in volume during immobilization was determined. The following tables (VII and VIII) show the amount of wasting with and without galvanism, with the decrease in volume expressed as a percentage of the volume of the hand before immobilization. Allowances had to be made for the subsidence

of œdema after removal of plaster, and measurements were not necessarily made on the days immediately preceding and following immobilization, so that the figures are not accurate beyond the decimal point.

TABLE VII.—IMMOBILIZATION WITH GALVANISM.

Case No.	*Period of immobilization in days after injury*	*Duration of immobilization in days*	*Decrease in volume as percentage of volume of the hand*
1	38— 62	24	1
2	63—110	47	0
3	70— 93	23	0
4	97—111	14	0
5	165—216	51	0
6	170—192	22	0
7	179—230	51	0
8	183—247	64	0
9	200—258	58	5·0
10	204—301	74	5·0
11	226—238	12	0
12	272—286	14	0
13	335—391	56	0
14	442—456	14	0

TABLE VIII.—IMMOBILIZATION WITHOUT GALVANISM.

Case No.	*Period of immobilization in days after injury*	*Duration of immobilization in days*	*Decrease in volume as percentage of volume of the hand*
1	51—103	52	9·0
2	87—137	50	5·6
3	90—165	75	4·0
4	127—169	42	3·2
5	128—147	19	18·2
6	150—215	65	3·0
7	151—219	68	3·0
8	160—212	52	4·5
9	220—269	49	0·0
10	230—300	70	0·0
11	238—263	25	3·2
12	243—265	22	1·5
13	304—380	76	2·7

These figures were obtained from patients in whom there were variations in the time since injury, the duration of immobilization, the degree of wasting before immobilization, and the response to plaster fixation: one patient would use the hand freely, while another would tend to keep it immobile. Because of these variables, further analysis of the results would be fruitless, but the difference in the loss of bulk with and without galvanism is far too striking to be fortuitous.

Comparison between the data of Table VIII and fig. 16 suggests very strongly that immobilization without galvanic treatment aggravates wastage; but the data of Table VII show that in the majority of cases such wastage may be brought to a standstill by galvanism.

Effect of Galvanism on Recovery.

The *recovery* of bulk and power in these lesions was difficult to analyse, because it varies with the state of the muscle fibres and with the rate and degree of reinnervation. The latter in turn are dependent on many variable factors (E. Gutmann, 1942), and moreover the degree of reinnervation cannot be accurately measured as yet. The cases were put into the groups described according to the type and site of lesion and length of denervation, but even so there was not enough uniformity to make any quantitative assessment of results in the comparable groups; however, several tentative conclusions were drawn from such observations as could be made.

As a rule recovery in voluntary power and bulk occurred faster when a patient was receiving galvanism than when he was not. In 12 cases in which wasting was pronounced, return of voluntary power and of bulk were very poor. It also seemed that the delay between the appearance of motor unit action-potentials and the return of voluntary power was greater in these wasted cases. Some were receiving galvanism, but wasting had already occurred before galvanic treatment was begun. In all but 2 of these 12 cases the nerves had been sutured. Increase in bulk usually followed return of voluntary power, but in a few cases wasting continued after the onset of recovery. In only one case was an increase in bulk observed *before* return of voluntary power. When there was free use of the hand, and a good return of voluntary power, there was often an increase in bulk, whether or not galvanism was being given. In the 7 children studied (between 10 and 14 years of age) the lesions were favourable, and good recovery in power and bulk occurred, whether or not galvanism was given.

Lesions in continuity.—In axonotmesis (Seddon, 1943), a lesion in which the damage is sufficiently severe to cause degeneration of the axons but not to cause disorganization of the Schwann tubes, recovery of voluntary movement is soon followed by the power of independent control of individual muscles; this is due to the fact that the outgrowing fibres are directed down their original channels and reach their appropriate endings, and the pattern of motor and proprioceptive innervation is undisturbed. When, on the other hand, the lesion is a neurotmesis, there is mixing of the fibres at the site of lesion and attempts to contract one muscle produce contractions in others reinnervated by the same nerve. All the cases in Table IX were of lesions in continuity and it is presumed in those in which independent movements became possible, that the lesion was

predominantly axonotmesis, while in the remainder there must have been intraneural scar.

Table IX shows the relation of return of bulk to recovery of independent movements. Some cases were treated with and some without galvanism.

TABLE IX.

Case No.	*Independent movements*	*Increase in bulk*	*Galvanism*
1	Poor	Fairly good	+
2	Poor	None	−
3	Absent	Loss of bulk	−
4	Poor but present	Slow and slight	−
5	Fair	Slight	+
6	Fair	None	+
7	Fair	Fair	+
8	Fair	None	−
9	Moderate	Good	−
10	Fairly good	Good	−
11	Good	Good	+
12	Good	Good	+
13	Very good	Good	+
14	Very good	Good	+
15	Very good	Good	+
16	Very good	Good	−

There is a direct relation between return of independent movements and increase in bulk: when independent movements are good recovery of bulk follows whether or not galvanism is being given but, when return of independent movements is poor, there seems to be a greater increase in volume in those cases treated with galvanism.

Recovery after suture of the nerve.—In these cases independent movements were invariably poorly performed.

(*a*) *Recovery in muscles with little wasting in patients treated without galvanism.* In two cases of suture in which there was no gross wasting but galvanism was not being given, voluntary power did not return as well as was expected from the electromyographic findings and there was no increase in bulk.

(*b*) *Decrease in bulk in recovering cases not receiving galvanism.* In three cases not treated with galvanism there was a decrease in bulk even while voluntary power was returning.

(*c*) *Arrest of recovery on reducing frequency of treatment.* In one case when the frequency of treatment was reduced from six to three times a week the voluntary power, which had been increasing, remained stationary, and the volume of the hand fell slightly. The electromyographic findings showed no deterioration. Later, however, further progress in functional recovery was made.

These observations suggest that the prevention of wasting favours

recovery of power and bulk: that in cases of axonotmesis in which recovery of independent movements is good, increase in bulk occurs whether or not galvanism is given; that in cases of suture of the nerve or lesions in continuity in which recovery of independent movements is poor, galvanism favours recovery of power and bulk: and that in children and young adults who are constantly using their hands freely, good recovery may occur without the use of galvanism.

Illustrative Cases.

Case 1.—A man aged 33 sustained division of the right ulnar nerve just above the wrist. Treatment with faradism to the paralysed muscles was begun on the 16th day after injury, and both faradism and galvanism on the 19th day. He was admitted to the Wingfield-Morris Orthopædic Hospital on the 24th day, and was treated with 90 galvanic contractions to each muscle twice a day. Tolerance was good and there was no fatigue. Treatment was interrupted between the 57th and 64th days. On the 75th day the nerve was sutured, and the elbow and wrist were immobilized in plaster until the 108th day. During this time galvanism was continued except on five days. The wasting of the hand was very slight on admission (24th day). The volume of both hands varied considerably from day to day, but when the volume of the paralysed side was expressed as a percentage of the normal, the variation was less marked (fig. 17 B); there was a slight fall in volume until 50 days after injury. After this the volume remained more or less constant, but there was a slight fall during immobilization in spite of galvanic treatment being continued. (The appearance of a fall following removal of plaster is probably due to subsidence of œdema.) Treatment was discontinued after 133 days.

Thus it is seen that in spite of intensive treatment some wasting still occurred until the 58th day. After this time it was prevented so long as the limb was free, but although treatment was continued, immobilization caused further slight wasting.

In all figures showing volumes of both hands x = normal side and o = paralysed side.

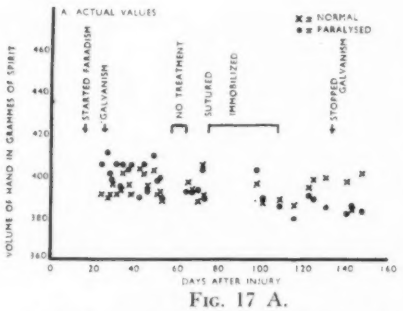

FIG. 17 A.

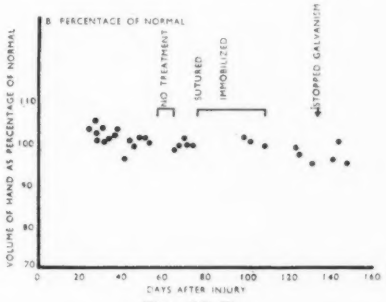

FIG. 17 B.

FIGS. 17 A and B (*Case* 1).—A = actual values. B = percentage of normal.

The figures show that only slight wasting occurred and this developed early after denervation and during immobilization.

Case 2.—A boy aged 16 years sustained a severe laceration to the right forearm and elbow with division of the median and ulnar nerves. The elbow and wrist

were immobilized in plaster from the time of injury until the 57th day and the hand was treated with daily galvanism from the 16th day. On the 133rd day a flap graft was made from the abdomen to the forearm, so that the hand was immobilized and was not treated in any way until the 147th day. The forearm was then detached from the abdomen, but galvanism was not given until the 154th day; it was again immobilized in plaster without galvanism from the 245th day to the 265th day. After this galvanism was given three times a week elsewhere, and after the 341st day galvanism was discontinued. No recovery in voluntary power occurred.

Result.—No volumetric measurement could be made in the first 40 days, but from the appearances of the hand it was apparent that only slight wasting had occurred. From 60 to 120 days after injury both hands grew and it can be seen from fig. 18 B that there was a slight relative increase in bulk on the paralysed side. There was a marked fall in the volume of the hand during the short period in which there was immobilization without galvanism. The effect of operative trauma cannot be ignored, but this was also present in the cases treated with galvanism during immobilization.

This case shows that galvanism was effective in preventing wasting from 38 to 128 days after denervation. It also shows an extremely rapid rate of wasting when no galvanism was given and the limb was immobilized.

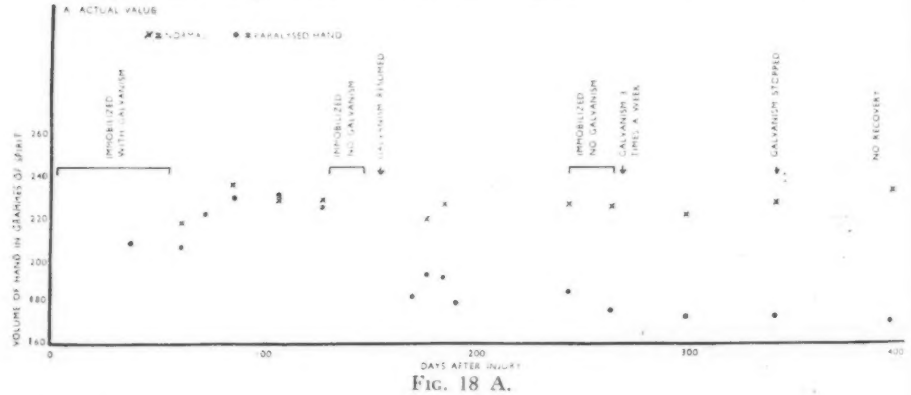

FIG. 18 A.

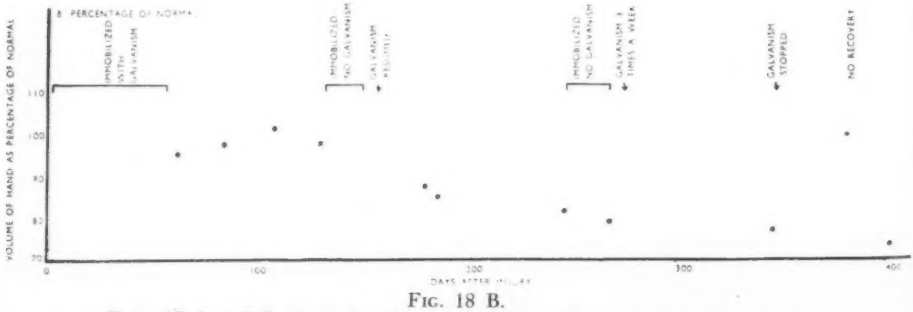

FIG. 18 B.

FIGS. 18 A and B (*Case* 2).—A = actual values. B = percentage of normal.

Case 3.—A boy aged 14 years sustained division of the ulnar nerve 3 cm. above the pisiform. He was admitted on the 3rd day after injury. The wrist only was immobilized in a small anterior plaster slab from the 3rd to the 50th day for the benefit of healing of the wound, but this did not prevent him from using the hand freely. He received passive movements and exercises daily, but no galvanism until the 50th day, when he started to have it daily in the usual manner.

On the 28th day a small skin graft was applied to the wound. There was complete paralysis with electrical reactions following the typical course of an early degenerative lesion. The electromyograph never showed any motor unit action potentials. On the 12th day fibrillation irritability was present, and by the 20th day a few fibrillation action potentials had appeared.

Result.—On the 3rd day there was no apparent wasting. Fig. 19 B, in which the volume of the hand is given as a percentage of the normal, shows that wasting started between the 5th and 6th days and proceeded fairly rapidly until the 20th day. From 24 to 58 days after injury readings had to be interrupted, but from the later readings it appears that wasting had continued at a slightly decreased rate. Although the actual decrease in bulk of the paralysed side was small, the loss relative to the normal growing hand was fairly large. This is the only case in which wasting immediately after injury could be observed. Wasting started five days after injury and progressed rapidly at first. There was no evidence of fibrillation irritability however until the 12th day. Without galvanism wasting was more rapid than in a comparable period when galvanism was being given (*see* Case 1).

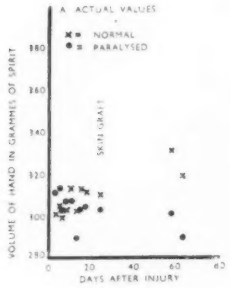

FIG. 19 A.

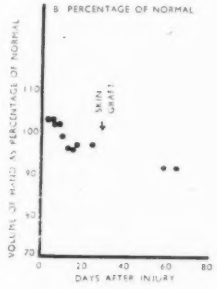

FIG. 19 B.

FIGS. 19 A and B (*Case* 3).—A = actual values. B = percentage of normal.

Case 4.—A man aged 20 years sustained division of the ulnar nerve 5 cm. below the medial epicondyle. The limb was immobilized in plaster until the 27th day after injury and from that day he was treated with massage, passive movements and exercises but no galvanism. The nerve was sutured on the 68th day, and the elbow and wrist were immobilized until the 119th day. Wasting was measured between the 27th and 154th days. There was rapid wasting between the 27th and 67th days. After the 68th day, on which the nerve was sutured, immobilization as well as denervation may have affected the wasting, so that no accurate conclusion can be made about the further course of wasting. This is a second case illustrating a more rapid rate of wasting when galvanism is not given.

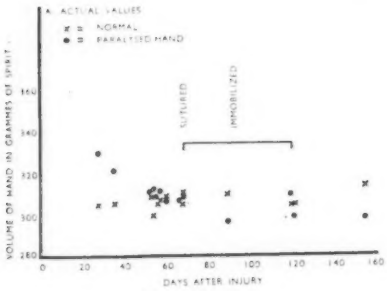

FIG. 20 A.

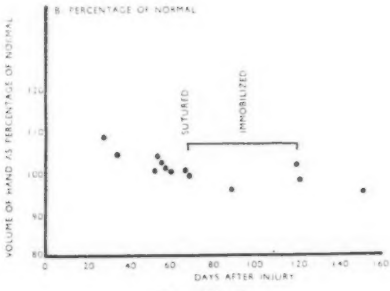

FIG. 20 B.

FIGS. 20 A and B (*Case* 4).—A = actual values. B = percentage of normal.

DISCUSSION.

The results of these observations are of necessity less accurate and informative than those of animal experiments, which include weighing and histological study of muscle. It is inevitable that with the methods used here any change in volume due to decrease in blood flow or to shrinkage of the skin and subcutaneous tissue will be recorded in addition to the muscle atrophy and this change might be considerable in a patient with both median and ulnar lesions. Furthermore there are obviously considerable variations in the volume of muscles in relation to the bulk of the whole hand, and a very large number of cases would have to be examined to eliminate this factor. Nevertheless, the method is reliable enough to establish certain facts, which are in keeping with the results of the most reliable animal experiments. They are, briefly, these:

(1) After denervation the volume of the hand decreases whether or not it is treated with galvanism.

(2) The rate of wasting is greatest early after denervation, but gradually falls off.

(3) If galvanism is not used, wasting continues until about 400 days. After this time there is no significant decrease in volume: atrophy is maximal.

(4) If galvanism is used the rate of decline in the 0-100 day period is significantly reduced.

(5) If galvanism is used, the decline in the volume of the treated hand ceases in the period 100 to 200 days and thereafter.

(6) Recovery of function is probably better in muscles in which wasting has been retarded.

(7) It appears that recovery of function is hastened when galvanism is given.

(8) During immobilization wasting is largely prevented by galvanism, but the rate of wasting without galvanism appears to be increased when the limb is immobilized.

Rate of wasting without galvanism.—In animals it has been shown that wasting begins a short time after denervation, the latent period varying with the species; the rate is rapid at first and gradually declines. (Langley, 1915; Audova, 1921; Chor, 1937; Gutmann and Guttmann, 1942.) In the cases reported here the onset was observed in only one case; wasting began between the 5th and 6th day after injury. It is interesting that fibrillation irritability did not appear until the 12th day and fibrillation action-potentials not until the 20th day after injury; thus the activity due to fibrillation, suspected by some as one cause of wasting, could not have been responsible for the wasting which occurred between the 5th and 12th days. The rate in Man is also greatest at first and gradually declines. The readings in Case 3 show that the volume of the hand fell most rapidly between the 6th and 20th days, and by 54 days the rate had decreased considerably. The combined results show that wasting continued until the 300 to 400 day period but after 400 days it stopped. At 258 days the rate of wasting was less than half that at 60 days. These findings indicate that measures directed to prevent wasting cannot be started too early. On the other hand they will still be of some value if started up to 400 days after denervation.

Gutmann (1942) found that when recovery was occurring increase in bulk appeared before the return of voluntary power. In this series, this was found in only one case and usually increase in bulk coincided with the return of voluntary power, rather than with reinnervation. In two cases wasting continued after recovery of voluntary power. These, however, were still in the early period of rapid wasting, and it is possible that wasting in the muscles not yet reinnervated was greater than the increase in bulk in the recovering muscles (Hines, Thomson and Lazere, 1942). The coincidence of increase in bulk with recovery of function suggests, but does not prove, that active use is responsible and should therefore be encouraged. On the other hand it is possible that both increase in bulk and recovery of voluntary power are separately dependent on an adequate degree of reinnervation.

Rate of wasting with galvanism.—The grouped results and records of individual cases show that galvanic treatment reduces the rate of wasting. This was found to be the case in animals by Fischer (1939), Hines (1942),

Hines, Thomson & Lazere (1943) and Gutmann and Guttmann (1942, 1944). The last two workers observed (1942) that in rabbits, even with massive doses of galvanism, wasting could not be completely controlled during the first fourteen days of denervation, and (1944) that in muscle treated for two months after denervation there was a loss of 17 per cent. of muscle volume. This is in keeping with the result found here that in the initial (0-100 days) period wasting occurred even when galvanism was being given, though it was considerably less than in the untreated cases. In the 100 to 200 day period and thereafter wasting in the treated cases was brought to a standstill. In two cases wasting was prevented at 40 and 50 days after denervation. In both the nerves were later found to have been completely divided so that reinnervation can be excluded.

Gutmann and Guttmann (1944) found that in rabbits the amount of wasting prevented was greatest in the first month and then became progressively less. From fig. 16 it is seen that from the 100 to 200 day period onward wasting is virtually prevented by galvanism; consequently the earlier it is given the greater is its total effect. These facts have a bearing on the treatment of nerve injuries. Under present conditions many patients with nerve injuries are treated for their wounds or fractures without any realisation of the urgent need for adequate physiotherapy, especially galvanism. It might be argued that at first the treatment of the wound is of primary importance. This is often true, but unless the site of the wound or fracture is a contra-indication, the paralysed muscles can generally be exposed and exercised with galvanism, while immobilization of the damaged zone is continued.

The duration of wasting and the effect of galvanism in the later stages of denervation are of importance in considering the treatment of patients with long-standing injuries in which there may still be some prospect of recovery. Until the 400th day period wasting continues without galvanism, but is reduced when galvanism is given. Therefore up to 400 days treatment is of value, even in the absence of reinnervation. Gutmann and Guttmann (1944) found similar results with late treatment and also noted that when treatment was instituted late after denervation the muscles at first responded poorly and became fatigued, but after 10 days the responses became brisker, fatigue was less marked and the current needed to produce a contraction became less. A similar phenomenon was often seen clinically at the onset of treatment; some muscles became fatigued after about 20 contractions but after a month's treatment the full 90 contractions could be given at one session without fatigue. Clinically, how-

ever, there was no obvious change in the character of the response and the threshold did not alter.

When galvanism was begun during the period of denervation no muscle showed any actual increase in bulk attributable to the treatment, so that the only beneficial effect demonstrated was the prevention of further atrophy which in the late stages is slight.

Effect of galvanism on recovery.—It would be useless to give galvanism if it had no beneficial effect on the ultimate functional recovery. Does it follow that control of wasting improves the prospect of restoration of function? Hines (1942) found that galvanic stimulation accelerated recovery of muscle mass and strength and Bowden and Gutmann (1944) showed that the degree of recovery of voluntary power after reinnervation is partly dependent on the condition of the muscle, and this deteriorates as duration of denervation increases. Moreover, the changes in muscle are at first reversible when reinnervation occurs: as the duration of denervation increases they become irreversible. In one long-standing case the changes were so gross that even with good regeneration of nerve down to muscle no recovery of motor power occurred. In the cases described here it was impossible to make an accurate assessment of the effect of galvanism because there were so many other factors influencing the rate, degree and quality of recovery but the electromyogram gave some indication of the time and progress of reinnervation and this helped in the observations on the effect of galvanism on recovery. In 12 cases with marked wasting, in some of which galvanism had recently been started, there was a long delay between the arrival of motor unit action-potentials and return of voluntary power and when recovery of function did appear it was poor, progressed slowly and there was little increase in bulk. In other cases it seemed evident that recovery of voluntary power and increase in bulk occurred faster when galvanism was being given at the time of reinnervation even when gross wasting had not occurred. This suggests that galvanism is beneficial to recovery in two ways, in preventing wasting and in assisting in re-education. This latter action is supported by the fact that recovery was benefited more in patients in whom control of the recovering muscles was poor, e.g. sutures of the nerves: those who used the recovering muscles freely and could control their independent action did well whatever the treatment.

In view of the findings of Bowden and Gutmann quoted above and those of Gutmann and Guttmann (1944) that in animals the difference in final recovery with and without galvanism is more marked in a long-standing case than one which recovers rapidly it is obvious that treatment

is of greater import in the lesion in which recovery is expected to be late.

In the 7 children studied good recovery occurred whether or not galvanism was given, though atrophy did occur. The fact that regeneration is relatively more rapid in young animals than in older ones (Hines, Thomson and Lazere, 1942) may be responsible, and as children find the treatment unpleasant it seems less strongly indicated than in adults.

Effect of immobilization.—Solandt, Partridge and Hunter (1943) found that immobilization of innervated muscles produced the same degree of atrophy in the first ten days as when the muscles were denervated but not immobilized; it is well known that the effect of immobilization on normal muscles can be considerable. Eccles (1941 and 1944) has shown that disuse atrophy is greatly reduced by electrical stimulation, especially if tension is produced in the muscle. Hines (1942) found that immobilization of denervated muscle did not affect the rate of atrophy, but did retard the rate of recovery of muscle mass and power. In contrast with these findings, our observations suggest that immobilization increases the rate of wasting when galvanism is not given. This may be because the animal studies were made early after denervation, or because some disuse wasting of normally innervated muscles occurred in the human cases. If, however, the wasting in man were due simply to immobilization of the innervated thenar muscles, the ulnar nerve being damaged but the median nerve intact, there should have been *increase* in bulk when the limb was mobilized again; this did not occur. When galvanism was given during immobilization, wasting was prevented in most cases so that the difference in rate of wasting brought about by galvanism seems to be even greater than when the limb is free. These findings indicate that if immobilization is necessary it should be minimal, that the patient should be encouraged to use the hand freely, and that wherever possible the denervated muscles should be exposed through windows in the plaster so that adequate galvanic treatment can be given. When splintage is necessary for the prevention or correction of deformities or the relaxation of paralysed muscles, care must be taken that active movement of the limb is not restricted.

Clinical Considerations.

Some of the patients included in this study received treatment only one to three times a week and by various techniques. Since they were usually out-patients volumetric readings could not be made frequently enough to justify pooling the results. Individual graphs show that their behaviour was more like that of untreated cases than of those receiving

daily galvanism under our supervision. In some a decline in volume occurred when in-patient treatment ceased.

Experimental workers have emphasized the importance of adequate strength of stimulus, frequency of treatment and number of contractions at each session. In their quantitative experiments (1944) Gutmann and Guttmann found that 20 minutes' treatment was superior to 10 minutes', but 30 minutes not much better than 20. Treatment for 20 minutes twice a week was definitely inferior to daily treatment; and a current that gave a feeble contraction was useless. Solandt, de Lury, and Hunter (1943) have found that the efficacy of daily treatment was proportional to the number of sessions, but not to their duration. Gutmann and Guttmann however, found short treatments of little value. The system of therapy chosen for the present work has been found to control wasting to a satisfactory extent though not fully and since poor results were obtained when treatment was reduced, one is bound to recommend the adoption of nothing less than the full daily routine. If the results of Solandt and his co-workers are confirmed it might even be advisable for treatment to be given at short intervals during the day; to be practicable this would call for the manufacture and distribution to patients of simple galvanic machines that could safely be used at home. Solandt, de Lury and Hunter (1943) have suggested that sinusoidal current is of more value than galvanic; but according to Hines, Thomson and Lazere (1943) any current which produces a contraction is effective. It might be argued that treatment with galvanism requires the constant supervision of a trained physiotherapist because of the dangers of fatigue, over-stretching of muscles and burns, etc. The first two have been shown to produce no harmful effects when they occur during the course of treatment (Hines, 1942), and the patient is unlikely to burn himself if he is warned of the danger and how to avoid it.

All these results and conclusions are based on treatment of the small muscles of the hand. These are the most likely to benefit from treatment and it may well be that to be effective, treatment must be much more intensive on the bulkier proximal muscles of the limbs. Further work is being done on this question (Bowden; personal communication). There may also be variation in the effect of treatment in different muscle groups as Eccles has found to be the case in animals (1941).

To summarize the applications of these observations to clinical treatment it can be said that:

(1) Galvanism is of value in decreasing the rate of wasting.

(2) Its value in preventing wasting decreases as time since injury increases. After 400 days its action is negligible.

(3) It is beneficial to recovery.

(4) It should start as early as possible.

(5) There should be no break in continuity of treatment.

(6) It should be continued until return of voluntary control is adequate.

(7) It must be given in adequate intensity, frequency and numbers of contractions.

(8) It is especially valuable when immobilization is necessary, or when the period of denervation is long or return of independent movements is poor.

(9) It is less important in children and very active youths.

(10) When economic and other factors make satisfactory treatment difficult its value must be assessed in relation to the circumstances of the individual.

Summary and Conclusions.

In the treatment of peripheral nerve injuries one problem is to maintain the denervated tissues in good condition so that when reinnervation occurs recovery of function will be as good as possible. In animals the condition of the muscle has been shown to be favourably influenced by galvanism.

This investigation was designed to show the effect in Man of such treatment as can reasonably be given clinically. Groups of patients with ulnar nerve paralysis have been treated with and without galvanism and the progress of wasting in the hand has been followed. The wasting has been measured volumetrically by immersing the hand in alcohol up to a constant level on the wrist and weighing the displaced fluid. Changes in bulk of the hand but not the absolute amount of wasting of muscle can be measured by this method. Changes in the bulk of the hand with and without galvanism have been studied (1) during denervation without immobilization, (2) during denervation with immobilization, and (3) during reinnervation.

The following conclusions have been reached:

(1) The volume of the hand is subject to considerable variation but large changes are brought about only by abnormal conditions such as heating the body to produce a high degree of vasodilatation. The variation in volume due to normal influencing factors such as manual work and small changes in temperature is not large, but it means that a single reading is not entirely reliable. There is, however, a direct if not absolute correlation between the changes in volume of the two hands of the same

subject. An adequate correction for the normal variation in the volume of the paralysed hand may therefore be made by measuring the volume of the normal hand as well.

(2) For a short period after denervation the volume of the hand decreases whether or not galvanism is given. The rate of decrease is greatest early after denervation and gradually becomes less as time goes on.

(3) When no galvanism is used wasting continues for about 400 days: after this time the volume remains constant.

(4) If galvanism is used the rate of wasting is decreased in the period 0 to 100 days and wasting ceases in the 100 to 200 day period and thereafter.

(5) Recovery of function is probably better in muscles in which wasting is slight and galvanism appears to aid voluntary action of the muscle when given at the time of reinnervation.

(6) Immobilization appears to increase the rate of wasting when galvanism is not given, so that the decrease in wasting attributable to galvanism is even greater than when the limb is free.

(7) In the few children studied recovery of power and increase in bulk were satisfactory whether or not galvanism was given.

(8) The findings support the use of galvanism in the care of denervated muscle but to be fully effective treatment should be without a break and adequate in intensity, duration, frequency. These results have been obtained from the treatment of small muscles: the behaviour of larger muscles may prove different.

I wish to thank Professor H. J. Seddon for his constant help, and for making the work possible: Mr. P. B. Medawar for invaluable aid in the statistical analysis of data: Dr. K. Mendelssohn and Dr. D. S. Evans for constructing the measuring apparatus: Miss R. E. M. Bowden for the use of the electromyographic data and the physiotherapists and patients of the Wingfield-Morris Orthopædic Hospital for their co-operation.

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THE INTERRELATION OF THE STRIO-PALLIDUM AND THE THALAMUS IN THE MACAQUE MONKEY.

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Introduction.

In recent years a considerable interest has been shown in the fibre connections of the basal ganglia or strio-pallidum and their physiology. The book on the basal ganglia (*Publ. Ass. Nerv. Ment. Dis.*, 1942) amply demonstrates the revived study of the normal and pathological aspects of these large subcortical nuclei. The last important contribution to the fibre connections comes from Mettler (1945) in which he gives a survey of his experimental material of the last three years. Our experimental observations started in 1942 but had to be interrupted on account of the war. Thanks to the generous gift of 10 monkeys by F. A. Mettler at the beginning of 1945 it was possible to complete the work.

Since Wilson's classical paper on the corpus striatum (1913) the efferent connections of the pallidum have been considered to terminate mainly in the regio subthalamica including the nucleus ruber and substantia nigra. According to Wilson's description only a minor part of the strio-fugal fibres enters the thalamus. Furthermore Wilson denied the existence of any connections between cortex and striatum. Recent physiological observations, however, have demonstrated these connections (Dusser de Barenne, Garol and McCulloch, 1942; Garol and McCulloch, 1944). Anatomical evidence in favour of these physiologically demonstrable connections have been brought forward by Mettler (1942) and by Glees (1944). The pathways for the cortico-striate fibres are both the fasciculus subcallosus and the collaterals from the internal capsule into the corpus striatum. It is unnecessary to review here the whole of the extensive and often contradictory literature, since it has been dealt with by Wilson (1913), Mettler (1942, 1945) and Kennard (1944).

The present investigation has shown that the interconnection of the pallidum, thalamus and hypothalamus is far more extensive than was

hitherto thought. The anatomical basis of this close relationship helps considerably in the understanding of the physiological phenomena reported by Dusser de Barenne and McCulloch (1938); Mettler (1940); Dusser de Barenne, Garol and McCulloch (1942); Gerebtzoff (1941), and by Kennard (1944).

Review of the Relevant Literature.

The dorsal part of the thalamus (or thalamus *sensu strictiori*) has reached a considerable development in the mammalian brain. Certain nuclear groups are present and of a constant size in all vertebrates. Other nuclei, however, become differentiated only in higher mammals in relation to the development of highly mobile limbs and their capacity for skilled movements. The nuclei of the mid-line form a group which is relatively constant throughout mammals. Walker (1938) suggested that their function may be concerned with visceral sensibility. The postero-ventral thalamic nuclei, which receive impulses from the limbs, undergo a considerable increase, and in a similar way the lateral and medial geniculate bodies are elaborated with progressive visual and auditory development. The lateral nucleus of the thalamus receives fibres from the opposite dentate nucleus of the cerebellum via the brachium conjunctivum and projects these cerebellar impulses to the motor cortex. In primates a completely new set of nuclei is added to the thalamus in the pulvinar. The nuclei of the pulvinar do not receive sensory impulses directly from the subthalamic level but only impulses which have already passed through other thalamic nuclei, and they relay these to the cortex.

Besides this increase of sensory relay nuclei related to the development of limb movements and the increasing importance of the cerebral cortex in sensory experiences, two nuclear masses (anterior and medial nuclei) deserve special study in view of possible interconnections with the basal ganglia. These two nuclei have undergone considerable increase in size in later stages of mammalian evolution despite the fact that neither of them receives a main sensory system, while the centre median nucleus (a part of the medial nuclear group) is without demonstrable cortical connections. It is therefore not surprising that the suggestion has been frequently made in the literature that the anterior and some parts of the medial nuclear group project to the basal ganglia. The anterior nuclei of higher mammals have so much increased in size that they produce a frontal elevation of the thalamus, the tuberculum anterius. In mammals each anterior nucleus receives the large tract of Vicq d'Azyr or mammillo-

thalamic tract from the corpus mammillare. In reptiles the anterior nucleus is connected with the neo-striatum (Kappers, 1921) and even in mammals it is said to send fibres to the caudate nucleus (Sachs, 1909). This connection would be homologous with a corresponding tract in birds and reptiles, the tractus thalamico-striatalis. De Vries (1910) held the view that the connection of the anterior part of the thalamus with the caudate nucleus can easily be demonstrated in a human embryo of 13 mm. length, but the development of the anterior limb of the internal capsule in later stages of embryonic histogenesis makes these thalamo-caudate fibres less obvious. However, the increase in size of the mammalian anterior nuclei is probably not due to a more extensive projection upon the neo-striatum (if this exists at all) but to a cortical projection upon the gyrus cinguli.

The medial nucleus of the thalamus is topographically bounded by two tracts, the fasciculus retroflexus and the mammillo-thalamic tract. Kappers (1921) holds the view that a component of the medial nucleus, the centre median nucleus of Luys, projects upon the neo-striatum.

When attempting a theoretical approach to the question whether a relationship between the dorsal thalamus and the strio-pallidum in mammals exists it can be said that the comparative anatomy does not favour a considerable connection. The dorsal thalamus develops phylogenetically in direct proportion to the increase of the cerebral or neo-pallial cortex. The strio-pallidum, on the other hand, is already highly developed in primitive vertebrates and connected with the hypothalamus. From a phylogenetic survey the view may be held that so far as the diencephalon is concerned, a direct connection of the basal ganglia exists only with the subthalamic nucleus and the hypothalamus and that the connection with the dorsal thalamus is of an indirect nature and probably mediated via the mammillary bodies and the hypothalamus. Authors of neurological textbooks have always stated that the significance of the mammillo-thalamic tract rests in its importance of conveying olfactory impulses. This tract, however, increases in primates in size while the olfactory regions of the brain undergo a retrogression. But we must be cautious when judging the significance of brain nuclei and tracts in the light of phylogeny only. It may well be possible that the nuclei in the brain retain their topographical position and general configuration and change their functional significance.

Previous authors have suggested that the fasciculus thalamicus or Forel bundle H 1 interconnects basal ganglia and dorsal thalamus. Fibres from the basal ganglia running in the ansa and fasciculus lenticularis have

been described as merging in Forel's field H 1 from where they ascend in the fasciculus thalami. This fasciculus enters the dorsal thalamus by its medial or internal medullary lamina and possible connections could be made with the lateral or medial nuclei.

It is apparent that the study of normal material and the data of comparative anatomy offer several suggestions for an interconnection of basal ganglia and dorsal thalamus, but their verification can only be found in experimental evidence.

It is beyond the scope of this section to point out such experimental evidence brought forward by research on the interdependence of dorsal thalamus and cerebral cortex. In summarizing the most important facts it can be said that it is well established that the greater part of the nuclei of the thalamus undergo total degeneration when the areas of the cortex to which they send their axons, are removed.

This finding naturally provokes the suggestion that those nuclei or loosely arranged nerve cells of the thalamus which survive ablation of the cerebral cortex, have a connection with the strio-pallidum. To report these investigations in more detail the following observations have been made:

Following hemi-decortication in the chimpanzee and monkey, Walker (1935, 1938) found the rostral extremity of the ventral nuclear mass free from degeneration, suggesting that these cells do not project to the cerebral cortex. In the decorticated cat Waller (1937) also found the persistence of normal cells in the medial part of the anterior ventral nucleus. Ranson *et al.* (1941) in an experimental observation on a partially decorticated monkey, found that the ventral anterior nucleus was only partially degenerated and these authors suggest that, in the monkey at least, this nucleus not only maintains a connection with the cortex but that the surviving cells of the ventral anterior nucleus send their axons to the pallidum, which via the fasciculus lenticularis and the field H 1 of Forel establishes a connection in the reverse direction. Bard and Rioch (1937), however, found in a similar experiment on the cat that this nucleus was completely degenerated, and in the human case of cerebral sclerosis reported by Le Gros Clark and D. Russell (1940), in which the cortex had undergone almost complete degeneration while the basal ganglia remained apparently intact, the cells of the nucleus ventralis anterior had undergone total atrophy, thus supporting the view taken by Bard and Rioch.

The suggestion that the centre median nucleus sends its axons to the basal ganglia has frequently been made in the literature. Walker (1938)

found a complete degeneration of the nucleus in a monkey after decortication with marked damage to the basal ganglia, and, since in other experiments in which the caudate nucleus and putamen had only been partly destroyed, the element remained normal, he believed that it projected to the pallidal portion of the basal ganglia. On the other hand, in a human pathological case reported by Le Gros Clark and Ritchie Russell (1938) in which a vascular lesion had isolated the insular cortex and caused the destruction of afferent fibres, with only insignificant damage to the putamen, the centre median nucleus was found completely degenerated, suggesting at that time a projection of the centre median on to the insular cortex. But in the case reported by Le Gros Clark and D. Russell (1940) referred to above in which the insular cortex was also destroyed, the centre median nucleus persists undamaged, surrounded by areas of complete cell atrophy and dense glioses. Further experimental study of the monkey's brain by Le Gros Clark and Ritchie Russell in which the insular cortex was destroyed while leaving the basal ganglia intact also showed that the centre median nucleus remained intact. Ranson *et al.* (1941) describe the macaque centre median nucleus as relatively large and remaining entirely normal after decortication.

Material and Methods.

Nine monkeys have been used for the present study. O.M. 415, O.M. 430, M.P.L. 1, 2, 3, 4, 5, 6 and M.S.L. 1. The lesions have been caused by a high-frequency current passed through a unipolar electrode. Stimulation of the motor cortex was performed in each case.

The place of insertion of the electrode varies to some extent in the different animals and will be given in the individual case-history. For the staining of degenerated fibres the Swank-Davenport variation of the Marchi method was used.

The following abbreviations are used in the diagrams and figures:—

a.	= ansa	l.n.	= nucleus lateralis
a.c.	= anterior commissure	m.b.	= mammillary body
a.n.	= nucleus anterior	m.n.	= medial nucleus
c.	= caudate nucleus	m.th.tr.	= mammillo-thalamic tract
c.c.	= corpus callosum	o.ch.	= optic chiasma
c.p.	= cerebral peduncle	o.tr.	= optic tract
e.	= external div. of globus pallidus	pall.	= globus pallidus
		put.	= putamen
f.	= fornix	s.n.	= subthalamic nucleus
hip.	= hippocampus	s.nig.	= substantia nigra
i.	= internal div. of globus pallidus	v.a.n.	= nucleus ventralis anterior
		z.i.	= zona incerta

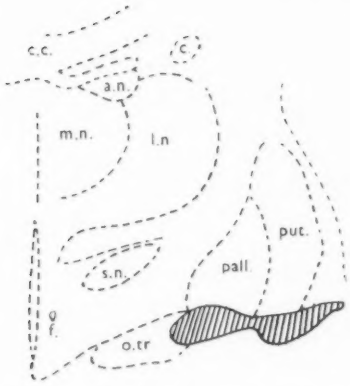


FIG. 1a.—O.M. 415. (For Figs. 1b, 1c of O.M. 415 *see* Plate XX.)

O.M. 415.—Operation 5.5.43. * 30.5.43.

The asterisk indicates the date the monkey was killed.

The electrode was inserted 1·8 cm. deep through the superior temporal gyrus 1 cm. below the central fissure.

Localization of lesions.—The sections reveal a well-defined lesion involving the anterior ventral part of the right putamen and the lower ventral part of the lateral and medial division of the globus pallidus including slight damage to the right optic tract.

Course of degeneration.—Histological examination gives the following picture: Marchi degeneration can be traced into the ansa lenticularis, fasciculus lenticularis and into the pallido-subthalamic tract. The degeneration of the ansa was caused by direct injury as it emerges from the external and internal lamina of the lentiform nucleus. The degenerated fibres which cross the mid-line within Meynert's commissure reach the opposite medial division of the globus pallidus. Some fibres of Meynert's commissure turn dorsally through the internal capsule and become collected again in Forel's field H 2. The Marchi granules can be followed through Forel's field 1 and 2 to enter the ventral nucleus of the thalamus of the opposite side. The lesion within the ventral part of the lateral and medial division of the globus pallidus caused a very distinct fibre degeneration which can be traced dorsally running mainly in the internal medullary lamina and the lamina accessoria. When the degenerated fibres reach the level of the internal capsule they become collected into distinct bundles and penetrate among the fibres of the internal capsule. On reaching the medial side of the internal capsule the fibres converge to form a conspicuous bundle and contribute to the greater part of the fasciculus lenticularis. The degenerated fibres run dorsally to the subthalamic nucleus and enter the field of Forel. Here the fibres form a well-defined loop and then turn into the fasciculus thalamicus. From this fascicle the fibres scatter diffusely within the lateral ventral

PLATE XX.

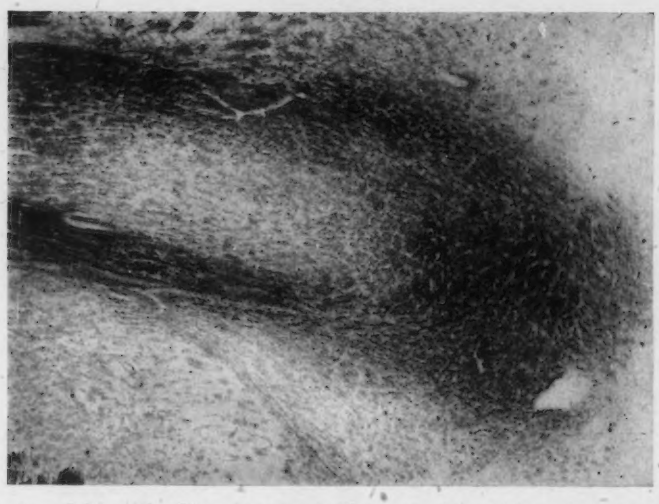


FIG. 1B.—O.M. 415. The photograph illustrates the position of the lesion and the resulting Marchi degeneration. The efferent pallidal fibres pierce the internal capsule and join to form a part of the fasciculus lenticularis. The clear space between the internal capsule and fasciculus lenticularis on the right side indicates the position of the subthalamic nucleus. × 14·5.

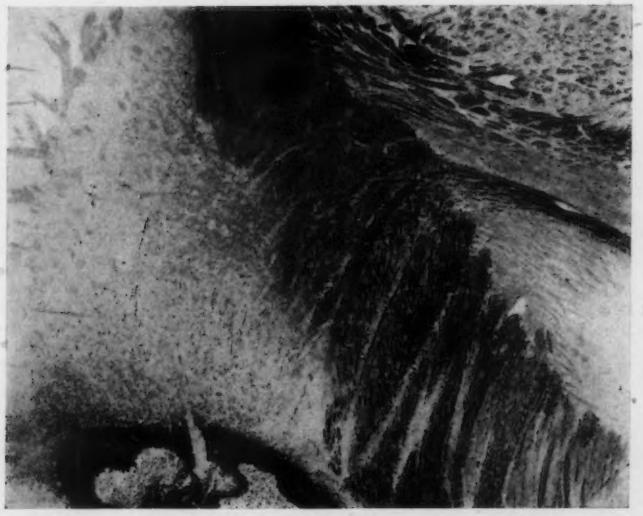


FIG. 1C.—O.M. 415. The photograph shows the degenerated fibres of the fasciculus lenticularis entering Forel's field. The greater part of fibres turns from here dorsally and laterally into the fasciculus thalamicus. × 18.

To illustrate article by P. Glees.

thalamic nucleus, but not all the fibres of Forel's field enter the fasciculus thalamicus – a small but distinct proportion can be traced ventrally into the homolateral side of the hypothalamus via the pallido-hypothalamic tract.

Besides the distinct bundles forming the ansa and fasciculus lenticularis numerous degenerated fibres cross the internal capsule directly into the subthalamic nucleus and ventral thalamic nucleus. These direct interconnecting fibres are the "Kammfasern" of German authors. Most fibres which enter the subthalamic nucleus pierce the internal capsule ventrally. The direct fibres which pass into the ventral thalamic nucleus enter more dorsally to the fasciculus lenticularis.

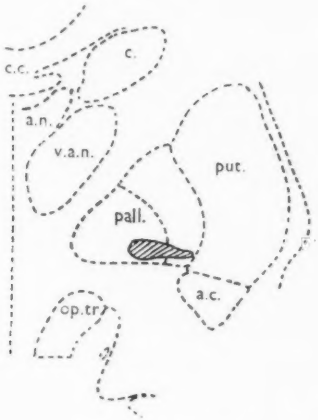


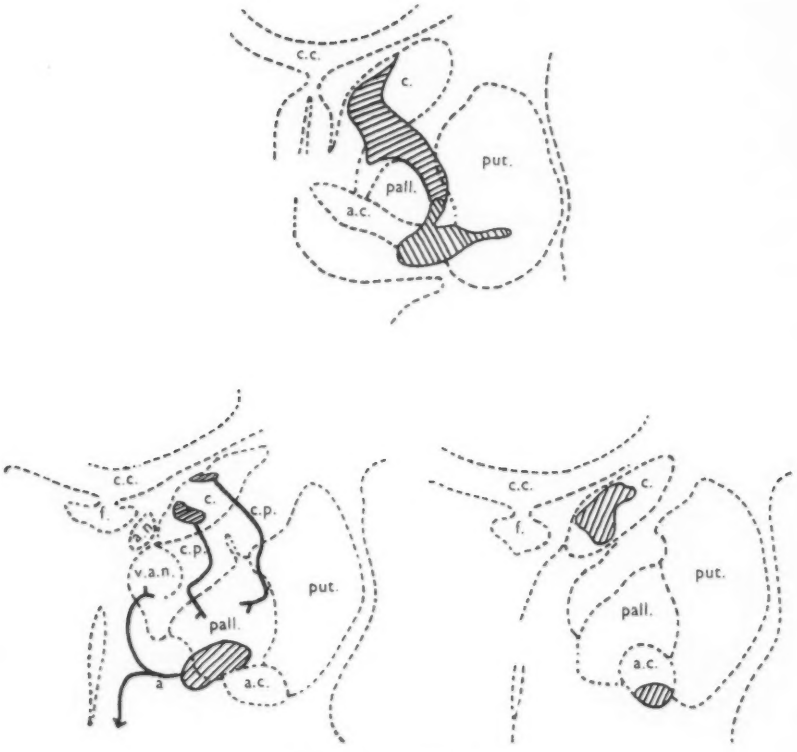
FIG. 2.—O.M. 430.

O.M. 430.—Operation 29.9.44. * 16.10.44.

The electrode passed through the Sylvian fissure 1 cm. anterior to the central fissure.

Localization of the lesion.—The greater part of the 4 mm. large lesion is within the internal pallidal segment and involves a small part of the external segment.

Course of degenerated fibres.—From the internal division of the pallidum numerous degenerated fibres join to form the ansa lenticularis. These ansal fibres sweep medially round the anterior limb of the internal capsule and ascend laterally to the inferior peduncle of the thalamus. A great number of fibres end in the ventral anterior nucleus of the thalamus, while others ascend dorsally into the stratum subcaudatum of Sachs. The fibres then turn medially and enter the habenular tract. Degenerated ansal fibres cross the descending pillars of the fornix and form a conspicuous pallido-hypothalamic tract. Degenerated fibres can be followed through the fasciculus lenticularis into Forel's field.



FIGS. 3, 4, 5.—M.P.L. 1.

M.P.L. 1.—Operation 12.4.45. * 25.4.45.

The electrode passed through the superior temporal gyrus.

Localization of lesion.—The lesion involves the anterior medial part of the pallidum, a small part of the anterior commissure, the medial part of the anterior limb of the internal capsule and the head of the caudate nucleus.

The lesion in the head of the caudate nucleus, caused by vascular occlusion divides into two parts further caudally. Fibres from the dorsally situated vascular softening pass through the internal capsule and enter the lamina medullaris externa pallidi while the fibres from the ventral lesion mingle with the internal capsule fibres and enter the medial division of the pallidum directly from the internal capsule.

Degenerated fibres of the ansa terminate in the ventral anterior thalamic nucleus and in the hypothalamus.

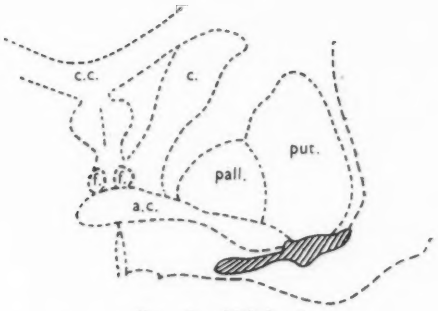


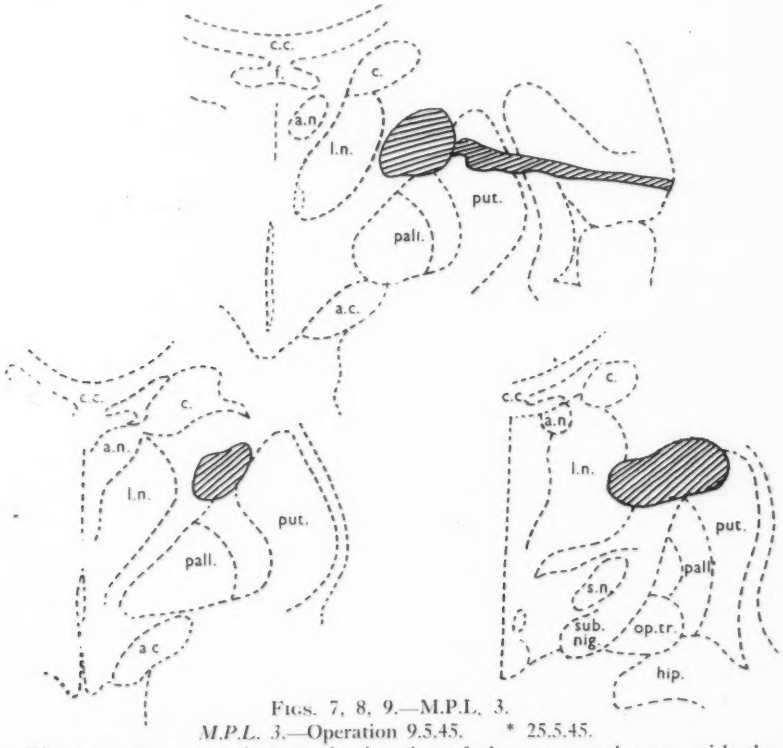
FIG. 6.—M.P.L. 2.

M.P.L. 2.—Operation 20.4.45. * 10.5.45.

The electrode passed through the superior temporal gyrus.

Localization of lesion.—The lesion extends from the lateral and ventral border of the putamen into the ventral area of the brain below the anterior commissure. A softening of the internal division of the pallidum caused an additional fibre degeneration. Degenerated ansal fibres pass into the habenular tract, the anterior ventral and some into the anterior thalamic nucleus.

Degenerated fibres of the fasciculus lenticularis enter the field of Forel and descend into the hypothalamus.



FIGS. 7, 8, 9.—M.P.L. 3.

M.P.L. 3.—Operation 9.5.45. * 25.5.45.

The electrode passed through the junction of the pre-central gyrus with the Sylvian fissure.

Localization of lesion.—The lesion involves the internal capsule the upper part of the pallidum and putamen and an infringement of the lateral thalamic nucleus.

The degenerated fibres from the putamen pass into the external medullary lamina of the lentiform nucleus and terminate in the external and internal division of the pallidum.

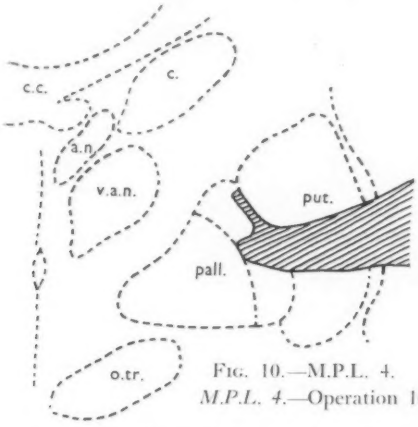


FIG. 10.—M.P.L. 4.

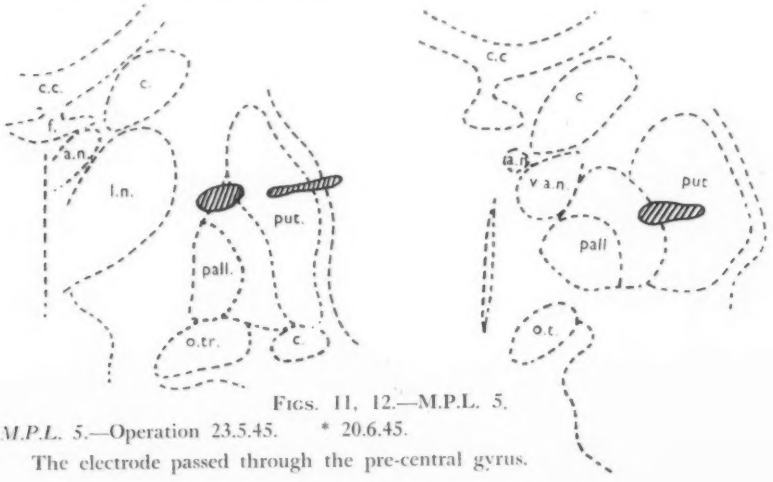
M.P.L. 4.—Operation 16.5.45 * 5.6.45.

The electrode passed through the lateral part of the pre-central gyrus.

Localization of lesion.—The lesion involves the putamen and the external division of the pallidum.

The putamen projects upon the external and internal division of the pallidum. The ventral half of the external medullary lamina is mainly composed of fibres originating in the putamen. The ventral half of the internal medullary lamina is composed of fibres from the external division of the pallidum.

The external division helps to form the fasciculus lenticularis, and contributes to the pallido-hypothalamic tract. More caudally the efferent fibres of the external division terminate in the subthalamic nucleus.



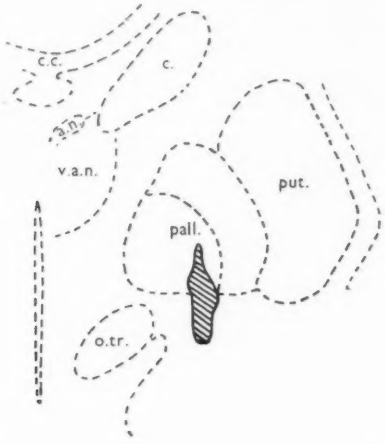
FIGS. 11, 12.—M.P.L. 5.

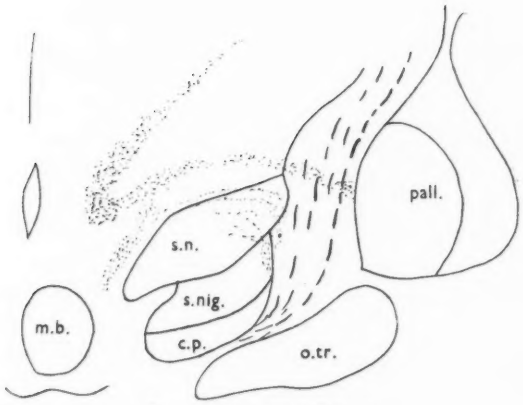
M.P.L. 5.—Operation 23.5.45. * 20.6.45.

The electrode passed through the pre-central gyrus.

Localization of lesions.—The first lesion occupies equal parts of the putamen and pallidum. The second extends over the upper half of the putamen and external division of the pallidum and infringes the internal capsule.

The putamen projects upon both the external and internal divisions of the globus pallidus. The external division of the pallidum projects upon the subthalamic nucleus, the hypothalamus and sends fibres into Forel's field and habenular tract. The motor cortex sends fibres into the putamen via the external capsule and fibres into the pallidum via the external medullary lamina of the lentiform nucleus.





FIGS. 13, 14.—M.S.L. 1.

M.S.L. 1.—Operation 24.8.45. * 14.9.45.

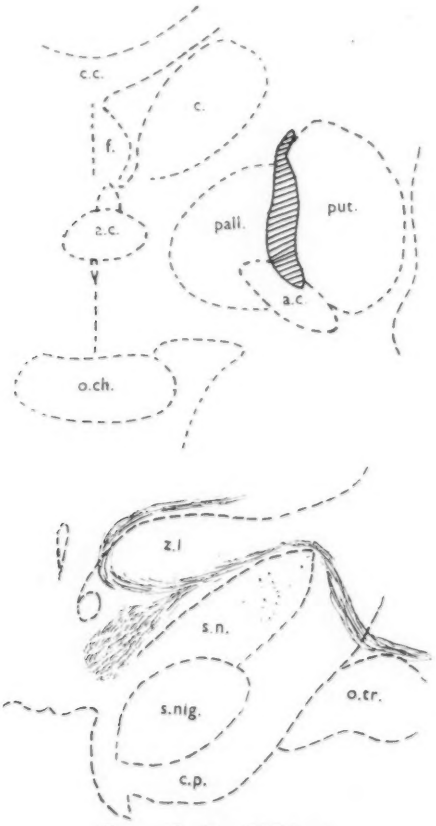
The electrode passed through area 6 of the cortex.

Localization of lesions.—Two lesions of the internal division of the globus pallidus were made. The more ventral lesion extended into the amygdaloid complex.

The internal division of the globus pallidus projects upon the anterior ventral nucleus of the thalamus. The pallido-hypothalamic tract connects the pallidum with the hypothalamus. The subthalamic nucleus receives direct fibres from the internal pallidal division.

From Forel's field fibres turn into the lateral thalamic nucleus via the fasciculus thalamicus. Other fibres from Forel's field are distributed in a region lateral to the mammillary body and as far caudally as the interpeduncular nucleus.

Lesion of the cortex, area 6.—A small but very distinct bundle of degenerated fibres passes into the internal capsule. Some of these fibres pass into the external division of the pallidum and enter via the dorsal part of the external medullary lamina of the lentiform nucleus. (Lesion of the Eortex was caused by the needle tract.)



FIGS. 15, 16.—M.P.L. 6.

M.P.L. 6.—Operation 28.8.45 * 2.10.45.

The electrode passed through the pre-central gyrus, the dorsomedial edge of the putamen and caused a distinct lesion of the external division of the pallidum.

Course of degenerated fibres.—No fibres of the ansa are degenerated pointing

out that the ansa takes origin from the internal pallidal division only. The degenerated fibres from the external division form the fasciculus lenticularis and pallido-subthalamic fibres. Fibres from the field H of Forel enter the fasciculus thalamicus and a few fibres can be traced into the mammillary body. A great wealth of degenerated fibres is located between the mammillary body and subthalamic nucleus and many of those fibres can be followed to the level of the interpeduncular nucleus

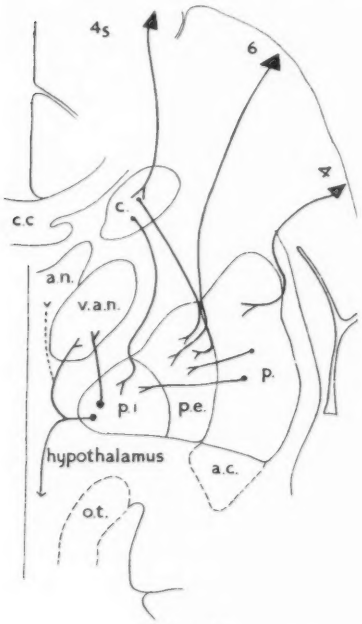


FIG. 17

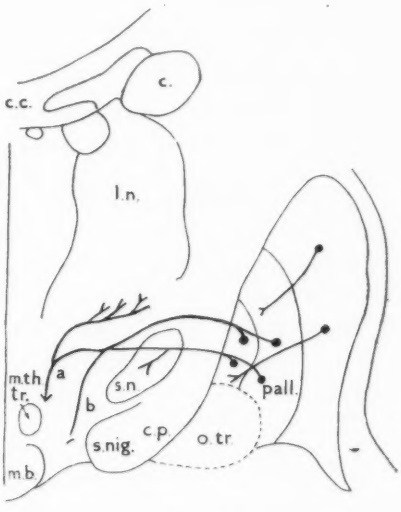


FIG. 18

FIG. 17.—Shows the interconnection of cortex, strio-pallidum, thalamus and hypothalamus at the level of the ansa lenticularis.

FIG. 18.—Shows the efferent fibres of the pallidum at the level of the fasciculus lenticularis.

"a" marks the fibres from Forel's field which descend into the mammillary body and the ventro-mediæ nucleus of the hypothalamus.

"b" marks the fibres which are scattered in the region between the mammillary body and subthalamic nucleus and which reach as far caudally as the interpeduncular nucleus.

DISCUSSION.

It is apparent from the fibre degeneration found in all nine monkeys that a considerable connection between the pallidum and the thalamus is present. The routes by which this connection is established are direct fibres and an ansal component to the ventral anterior nucleus and the fasciculus lenticularis via Forel's field and the fasciculus thalamicus to the lateral thalamic nucleus. The first experimental evidence for this

important connection came recently from Ranson and Ranson (1942). Conventional diagrams of the basal ganglia have always included a pathway from the pallidum into the thalamus without any definite evidence. The loop-like connection within Forel's field between the fasciculus thalamicus and fasciculus lenticularis is indeed difficult to recognize in normal material. The reason for this type of connection may be the expansion of the zona incerta in a medial direction. The pallido-thalamic pathway is interesting anatomically but a far greater significance lies in its physiological importance. Dusser de Barenne, Garol and McCulloch (1942) when describing the suppression effect of certain cortical areas found by physiological methods that the suppression circuit passes from the basal ganglia through the thalamus in order to reach the cortex again. This connection can be mediated either by way of the fasciculus lenticularis, Forel's field and the fasciculus thalamicus to the lateral nucleus or by pallidal fibres which enter the anterior ventral nucleus directly or by the ansal component which ascends into the anterior and anterior ventral nucleus. The connection with the anterior and anterior ventral nucleus is established by the internal division of the pallidum only. The lateral thalamic nucleus receives pallidal impulses via the fasciculus thalamicus not only from the internal but also from the external segment of the pallidum. The projection of pallidal impulses via the fasciculus thalamicus to the lateral thalamic group of nuclei is of particular interest because the same region receives fibres from the cerebellum as well and sends its axons to the motor area of the cortex (Walker, 1938). The fact that the anterior ventral nucleus (a part of the lateral nuclear mass) receives pallidal fibres deserves attention. The nucleus according to Walker (1938) escapes degeneration after cortical ablation and it may well be that this nucleus has its main connections with the basal ganglia.

The pallido-hypothalamic fibres form a very conspicuous bundle and both the ansa and fasciculus lenticularis contribute to this tract. Some of these fibres enter the mammillary body. A route through which pallidal impulses after their relay in the hypothalamus may be conveyed to the dorsal thalamus is provided by the mammillo-thalamic tract and the periventricular system of fibres. A fair number of pallidal efferents are distributed in the region between mammillary body and subthalamic nucleus and reach as far caudally as the interpeduncular nucleus. The connections of the centre median nucleus have recently been clarified by Mettler and Marburg (1943) who found a well-preserved centre median nucleus in a human fœtus characterized by the absence of the cerebral cortex. Furthermore Mettler (1945) believes that the centre median nucleus projects upon the pallidum via the fasciculus thalamicus and fasciculus lenticularis.

The significance of the subthalamic nucleus within the interrelation of the strio-pallidum and thalamus can as yet not be ascertained due to the lack of information about its efferent connections.

The projection of area 4 to the putamen and of area 6 to the pallidum found in our Marchi material (M.P.L. 5 and M.S.L. 1) confirms the physiological observations by Garol and McCulloch (1944). Fibres from area 4 travel through the external capsule in order to enter the putamen, fibres from area 6 pass through the external medullary lamina of the lentiform nucleus to enter the pallidum. Caudato-pallidal fibres also descend into the pallidum via the dorsal half of this external medullary lamina.

The pallido-habenular fibres have been noted by Wilson (1913) and by Ranson *et al.* (1941). It is, however, possible, that these fibres originate in the amygdala and not in the pallidum. In favour of their pallidal origin is the fact, that even small lesions of the internal pallidal division cause degeneration in the habenular tract. In the monkey M.S.L. 1 the lesion extends into the amygdala and the resulting fibre degeneration in the stria habenularis is particularly well marked. Caution is necessary for the time being, before these fibres can safely be included in a diagram of pallidal efferents because it may well be that the fibres from the amygdala run through the pallidum thus explaining the fact that these fibres degenerated in a lesion of the pallidum only. Ranson *et al.* (1941) have also drawn attention to this possibility.

Recent findings by Mettler (1945), Ranson and Ranson (1942) and the present experimental observations point out that the thalamus is not only a sensory relay station for exteroceptive and proprioceptive stimuli but also receives a distinct portion of the pallidal efferents. These anatomical data support the physiological observations reported above by Dusser de Barenne and his school.

SUMMARY.

(1) Experimental lesions of the strio-pallidum were made in nine monkeys and the resulting degeneration was studied with the Marchi technique.

(2) Area 4 was found to project into the putamen, area 6 into the pallidum.

(3) The caudate nucleus and putamen send their fibres mainly into the pallidum.

(4) The internal division of the rostral part of the pallidum forms the ansa lenticularis which sends fibres into the ventral anterior nucleus and the ventro-medial nucleus of the hypothalamus. Some fibres of the internal division pass directly into the ventral anterior nucleus.

(5) External and internal divisions together form the fasciculus lenticularis and pallido-subthalamic fibres.

(6) The fasciculus lenticularis distributes numerous pallidal efferents into the lateral thalamic nucleus via Forel's field and the fasciculus thalamicus.

(7) Some fibres from Forel's field terminate in the mammillary body and hypothalamus while others end in the region between mammillary body and subthalamic nucleus as far as the level of the interpeduncular nucleus.

(8) The fibre tracts described above indicate a close interrelationship between the strio-pallidum, the thalamus and hypothalamus.

The author wishes to express his thanks to Professor W. E. Le Gros Clark and his technical staff for giving facilities in operating on two monkeys, O.M. 415 and O.M. 430. For the serial arrangement of the remaining material of seven monkeys I am indebted to Mr. Marsland and his assistants and to Miss A. Schey for the drawings and preparing of the manuscript.

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NOTE ON THE LATERAL GENICULATE BODY.

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THE diencephalic nuclei and their connections present some of the most difficult anatomical problems of the central nervous system. However, patient and careful work during the years preceding the war in this country and on the Continent, and in Australia and America, had done much towards the elucidation of this intricate subject. Much more remains to be done, and it is essential that the field should not be confused by misunderstandings. It is a pity, therefore, that in a recent paper (Cooper, *Brain*, **68**, 1946) a number of misconceptions and misinterpretations tend to obscure the subject for those who may not be very familiar with it. It seems to me advisable, therefore, to try to clarify some of the points at issue. Dr. Cooper, in her embryological studies, makes the interesting suggestion that the dorsal nucleus of the lateral geniculate body is a derivative of the lateral rather than the ventral nucleus of the thalamus. Unfortunately, however, she does not state the criteria by which she defines this nucleus. On topographical grounds there is no doubt that she has wrongly identified it in some of her sections. In her fig. 11, for example, the region indicated as lying on the ventro-lateral surface of the thalamus between the dorsal and ventral nuclei of the lateral geniculate body is certainly not the position of the lateral nucleus of the thalamus. There are also other errors of identification of the thalamic nuclei which may confuse subsequent workers in the field. Thus, her dorso-median (? = dorso-medial) nucleus in fig. 11 appears to be the dorsal part of the ventral nucleus, the nucleus in fig. 12 also called by this name is really the centre median nucleus (which becomes differentiated rather precociously in the human embryo), and her "ventral nucleus" apparently only refers to the ventro-medial element. As a matter of fact, the appearances shown in a series of human embryos in this department do seem to indicate fairly definitely that the dorsal nucleus of the lateral geniculate body becomes differentiated by the delamination of the superficial zone of the same nuclear mass which forms the ventral nucleus of the thalamus. It is certainly possible that part of the geniculate body is also formed from the pars posterior of the lateral nucleus, but it is perhaps much more likely that this region of the lateral nucleus is derived from the

anlage of the geniculate body. But the best evidence that the dorsal nucleus of the lateral geniculate body is morphologically a derivative of the ventral nuclear mass is found by examining insectivore brains. In some of these the distinction between the ventral nucleus and lateral nucleus of the thalamus is made very clear by cyto-architectural differences, and in this case the cell type of the dorsal nucleus of the lateral geniculate body is the same as that of the ventral nucleus of the thalamus. Further, in some genera (e.g. *Macroscelides*) there is no demarcation at all between the dorsal nucleus of the lateral geniculate body and the ventral nucleus of the thalamus (not even a definite intervening medullary lamina), except that the former receives the terminals of the optic tract.

In her discussion of the lamination of the lateral geniculate body Dr. Cooper quite rightly says that the optic tract fibres in the higher primates enter mainly over the convex anterior surface of the body, and notes that I had already pointed this out in correction of an earlier assumption (based on the appearance of coronal sections) that most gain entrance at the hilum. On the other hand, it would be a mistake to suppose that no optic fibres enter the region of the hilum, because in fact many do so. I would suggest, however, that Dr. Cooper misunderstands the relation of the termination of the optic tract to the laminar pattern of the lateral geniculate body. She says that, according to Thuma, the optic fibres enter the lateral convexity of the geniculate body in the cat, and she assumes on these grounds that the laminar folding in the geniculate body of the cat is identical in type with that in the higher primates. But the important point to notice here is that the convexity in the cat is formed by the equivalent of lamina No. 1 (containing large cells) which encloses within its concavity the *deeper* laminæ of small cells, while in the higher primates such as the monkey the convexity which receives most of the optic fibres is formed by the small-celled lamina No. 6 which encloses within its concavity the other *superficial* laminæ. Judging from the appearance of sections through the lemuroid lateral geniculate body, the same contrast with the higher primates occurs here. In other words, whether the situation is considered relatively to the optic tract or independently of it, the curvatures of the laminæ obviously are in contrary directions. Thus, after all, the terms inversion and eversion of the laminæ are not really "meaningless." Certainly the eversion of the laminæ of the monkey's geniculate body is a very real thing, as anyone can at once see for himself by studying appropriate sections, or even better by examining a reconstruction model. Incidentally, an ontogenetic eversion in the human lateral geniculate body (as indicated by the formation of a hilum)

was described several years ago by Brugi (*Arch. Ital. Anat. Emb.*, **42**, 1939, p. 439).

It is, of course, open to argument whether, in my essay on the morphology of the lateral geniculate body (*Brit. Journ. Ophth.*, May, 1932, p. 264), I may have tended to over-emphasize the morphological basis of this phenomenon from the point of view of its phylogenetic significance. On re-reading this essay now, fourteen years later, I think this probably was the case, for my later studies have made it more clear that the difference in the pattern of folding of the lateral geniculate body in lemurs and higher primates is perhaps not of a fundamental nature. Indeed, in some of the lemuroids an incipient eversion of the laminæ at the ventromedial part of the body is apparent, the main (inverted) part of the body showing a laminar conformation similar to that of the "cauda" of the human geniculate body. The degree of eversion in different primates is probably determined by growth pressure and depends (at least partly) on the size of the geniculate body in relation to the rest of the brain. It is for this reason that the eversion of the laminæ is so much more pronounced in the Old World monkeys than it is in man. It must be stressed that the analysis of the laminar pattern of the geniculate body is not easy and thus does require very considerable care. For one thing, the mode of entry of the optic fibres is in reality extremely complicated in relation to the laminæ. They certainly do not at their entrance have the simple relation to the laminæ depicted in the diagram (fig. 19) in Dr. Cooper's paper, and this diagram is unfortunately also somewhat misleading in its representation of the arrangement of the laminæ at the anterior margin of the geniculate body.

Dr. Cooper's interesting paper contains some misunderstandings which have led her by implication to misrepresent me rather seriously. Perhaps the most striking of these concerns her statements at the top of p. 236 in her paper. In referring to my microphotographs of sections through the geniculate bodies of both sides in a pathological specimen (*Brit. Journ. Ophth.*, May, 1932, p. 282) she says that "as the figures are presented it is not conceivable that in the right and left lateral geniculate bodies the swing of the curved laminæ should be over to the right on both sides," and "nor is it likely that the hilum should be on the left side in both right and left geniculate bodies." But in the legend under these two illustrations it is specifically stated (in order to avoid just such a misunderstanding) that "In both cases the lateral aspect is towards the right."

Notices of Recent Publications.

The Cortex of Galago: Its Relation to the Pattern of the Primate Cortex. Gerhardt von Bonin. University of Illinois Press, Urbana, Ill. 1945. Price $1.50.

The brain of Galago, one of the lemurs, conforms to the pattern of the primate brain. In this admirable and philosophic monograph the components of this pattern are described, and the bearing of the author's study upon the larger problem of cortical evolution are discussed. He concludes that "as we ascend the evolutionary scale, the cortex assumes increasingly a structure which may be interpreted as leading to increased degrees of indeterminacy. It may be that it is cortical structure which determines why we instinctively rely on the 'truth' of our perceptions of the outer world but feel free and responsible for our actions."

L'Hypertonie de Décérébration chez L'Homme. P. Mollaret et I. Bertrand. Masson et Cie, Paris 1946. Price 180 francs.

Neurologists in this country will welcome the reappearance of the admirably produced neurological monographs published by Masson, and containing those notable contributions from our French colleagues which we have found so valuable and inspiring in the past.

The present monograph gives a summary of recorded cases of decerebrate rigidity in man with critical commentary, a brief account of the experimental physiology and of the anatomy of decerebration, and a detailed account of a carefully studied case of what in this country would be called Parkinsonian rigidity. This clinical state the authors submit as one of decerebrate rigidity in man, but it appears to show so few of what we accept as the cardinal features of this state as seen in the experimental animal that the attribution will not command a general assent. Nevertheless, the monograph is valuable as a record of the relevant facts of clinical observation in respect of "decerebrate rigidity" in man.

Voies et Centres Nerveux. J. Delmas et A. Delmas. Masson et Cie, Paris 1946. Price 270 francs.

This simple and clearly written monograph is submitted as an anatomo-physiological introduction to neurology. Its most successful chapters are those dealing with the spinal cord brain-stem and cerebellum. On the cerebral cortex it is somewhat out of date and takes no account of modern knowledge of the motor and sensory regions. Its balance is anatomical and within the limits set by its authors it will be found an excellent elementary introduction to those structural details that are essential to the clinical neurologist.

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